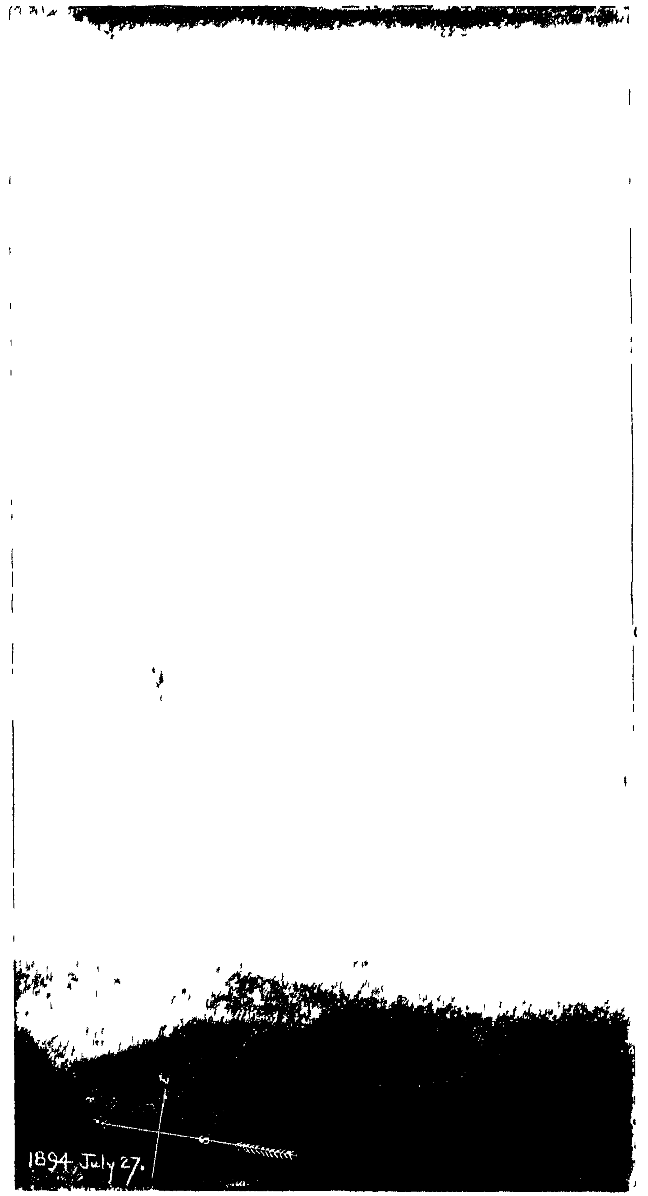


PLATE I THE METEOR OF JULY 27, 1894
Drawn by CHAUNCEY M ST JOHN

CONTRIBUTIONS FROM THE LICK OBSERVATORY No 5

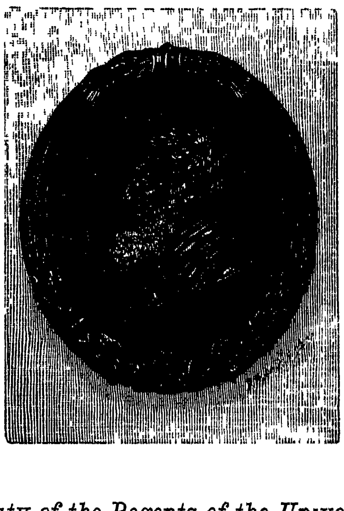
METEORS AND SUNSETS

OBSERVED BY THE ASTRONOMERS OF

THE LICK OBSERVATORY

IN

1893, 1894, AND 1895.



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A J JOHNSTON SUPERINTENDENT STATE PRINTING

1895

ORGANIZATION OF THE LICK OBSERVATORY

Hon T G Phelps, Hon C F Crocker, Hon C W Slack,
Committee of the Regents on the Lick Observatory

Martin Kellogg .... *President of the University*

Edward S Holden .... *Director and Astronomer,*

J M Schaeberle .... *Astronomer,*

W W Campbell .... *Astronomer,*

R H Tucker .... *Astronomer,*

W J Hussey .... *Astronomer,*

Allen L Colton .... *Assistant Astronomer,*

Robert G Aitken .... *Assistant Astronomer,*

C D Perrine .... *Secretary and Assistant Astronomer*

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

THE METEOR OF JULY 27, 1894.

By EDWARD S HOLDEN

TABLE OF CONTENTS

THE METEOR OF JULY 27, 1894.

By Edward S. Holden.

SECTION I.

INTRODUCTION.

This remarkable meteor was seen over a large part of California about 7^h 30^m, Pacific standard time, on the evening of July 27, 1894. A first inspection of the numerous reports of its fall shows that it entered the earth's atmosphere somewhere near the zenith of Merced, and fell vertically, or nearly so. It is the object of this paper to collect the numerous observations and to determine the path of the fire-ball; and also to give a description of the remarkable clouds which were left by the body after explosion, and which were visible for more than half an hour afterwards. The present report is intended chiefly for distribution to those persons in California who observed the meteor, and who were kind enough to send their observations to the Lick Observatory. For that reason it is given in considerable detail, and at much greater length than the purely scientific results warrant. The short sections III–VI contain most of the definite results.

Though many reports of observations were received at the Lick Observatory, it is singularly disappointing that all of them, taken together, do not give satisfactory data for an accurate determination of the meteor's orbit. The required data are extremely simple. Each observer should note (1) the altitude and azimuth (bearing) of the point where the meteor *burst*, (2) the same quantities for the point where the meteor *disappeared* (was dissipated). These data give for each observer a great circle in the sky, which corresponds to the apparent path of the meteor. All such circles (prolonged) meet in a point—the radiant point—which corresponds to the point where the meteor entered the earth's atmosphere. The position of this point on the celestial sphere, combined with

the position of the earth in its orbit at the time, enables the orbit of the meteor in space to be calculated. If each observer had also noted the interval of time which elapsed between the flash and the report, results of interest might have been obtained.

The very complete observations at the Lick Observatory serve to fix with great precision the place where the meteor burst; the point where it disappeared is less well determined. Several other stations also give a portion of the data with considerable accuracy. This is especially the case for College Park (Professor AITKEN), Carson (Professor FRIEND), Palo Alto (President JORDAN and Professor HUSSEY), Chabot Observatory (Mr. CARLTON and Mr. BURKHALTER), Los Gatos and Santa Clara (Mr. BRAY), San José (Mr. HERRING and Mr. HERROLD), Merced (Mr. JOHNSON and Mr. STONEROAD). No stations, except Mount Hamilton and College Park,* give complete data, however, and it is unfortunate that more accurate observations of direction are not available at stations in and about Merced. The necessary data must be obtained, as well as possible, from a combination of the reports at hand. The weak point of all the data is the position of the meteor at the end of its fall. A glance at the frontispiece shows why this is so. The meteor divided into (at least) two parts here, and some observations refer to one part, some to the other. The main downrush of the meteor was (in the frontispiece) nearly vertical. But a line joining the point of bursting with the point where the bright zigzag streak disappeared is not so. This streak was, loosely speaking, *southwards* from the path. Different observers at different stations have described sometimes the position of this zigzag streak, sometimes the end of the general downrush, as the end-point of the meteor's path. Most of these descriptions are in general terms, not accompanied by accurate measures, and it has not been possible to properly separate the data referring to each part.

The observed differences of time between the instant of explosion (which I call II) and the time when the sound of

*These two stations lie so nearly in the same direction from the meteor that the data derived from them alone are not sufficient to fix the radiant point.

the explosion reached the observer (IV), multiplied by the velocity of sound in air, if known, would give the distance of the meteor from the observer at the time II, measured in a straight line. The velocity of sound is usually expressed by the following equation, in which v is the velocity in feet per second, t is the temperature Fahrenheit.

$$v = 1088.3 \sqrt{1 + 0.002036\,(t - 32)}$$

At 32° Fahr., v = 1088 feet per one second
At —100° Fahr., v = 931 feet per one second
At —193° Fahr., v = 800 feet per one second
At —270° Fahr., v = 675 feet per one second

According to Professor FERREL (Report C. S. O. 1885, part 2, page 38) the limit of the earth's atmosphere is not far from 37 miles. The phenomena of twilight indicate that it extends to 45 miles, as FERREL remarks on p. 74. Beyond the limit, wherever it may be, the temperature is that of space, say —273° C., or —461° Fahr. From the earth's surface upwards the temperature diminishes at the rate of 28°.3 Fahr. for each mile of ascent.

A very interesting experiment by MM. GUSTAVE HERMITE and BESANÇON in 1893,* showed that a thermometer marked a temperature of —51° C. at 12,500 metres (in a balloon) and that the diminution of temperature was 1° C. per 186 metres of ascent.

The place where the meteor of July 27 exploded was 28 miles above the earth's surface, and 59.25 miles distant in a direct line from Mount Hamilton (0.8 mile high). The sound of the explosion required 390^s.7 to reach us. According to the formula previously given (the velocity of the sound being 800.5 feet per 1^s) the mean temperature of the air along its path must have been —193° Fahr. This mean temperature must have corresponded to a mean height of about 13.6 miles, or 21,888 metres. According to the experiments of M. HERMITE, the temperature at that height should have been about —101° C., or —150° Fahr. It is not certain that the formula represents the velocity of sound at extreme temperatures, since it was derived from experiments at ordinary temperatures, or rather from theoretical considerations based on such experiments. If we had *accurate* observations of the meteor through-

***L'Astronomie*, 1893, page 217.

out its course, it would be practicable to determine the velocity of sound experimentally when the path of the meteor is once known

The meteor was very generally observed throughout California, owing to its great brilliancy, to the beautiful and persistent cloud forms which it left behind it, to the clear skies then prevailing, and to the favorable hour of its appearance The newspapers contained a number of observations, a very complete and important series was made at Mount Hamilton by seven observers, many excellent observations have been sent to the Observatory by our correspondents*, and we have received, by the kindness of Hon C F CROCKER and Hon A N TOWNE, a large number of reports from the agents of the Southern Pacific Company Through the courtesy of Mr JAMES A BARWICK, U S Weather Bureau, Director of the State Weather Service at Sacramento, we have received copies of all the reports from his observers in California and extracts from a great number of California newspapers Hon R THOMPSON, of San Francisco, observed the meteor at Vallejo (see his report in Section II) He also collected a number of important reports from correspondents throughout the State, and has been kind enough to transfer them to the Lick Observatory They will be found in their appropriate places in this book

I have to thank Professor H A NEWTON, of Yale College, for advice freely given upon doubtful points

In order to have a definite nomenclature, let us take the following scheme of abbreviations

I is the time at which each observer first saw the meteor. (I is *before* the time of explosion in several cases)

II is the absolute time at which the meteor exploded (It is *about* $7^h\ 30^m$ Pacific standard time, about this time the bluish cloud A and the reddish clouds B and C were formed. See under *b*, below)

III is the time of disappearance of the meteor itself to each observer

IV is the time at which each observer heard the noise of the explosion which took place at the time II IV — II multiplied

*Section II, immediately following, contains a selection of the observations best suited to determine the position of the meteor, and Section VII is entirely devoted to reports of observations

by the velocity of sound gives the distance of the meteor from the observer

There were two sounds heard by some observers

(*a*) A hissing sound before the explosion at II

(*b*) A rumbling sound, which was due to the explosion at II

It is probable that there was not a single definite time of a single explosion, but that a series of explosions occurred as the meteor was moving in its path, and that these explosions were heard as a rumbling sound (See the excellent reports of Mr JOHNSON and Dr O'BRIEN, of Merced, among others) Moreover, it is not unlikely that there were also echoes of the true explosions I myself heard three sounds, and a number of others report this fact also

Let us call—

(A) the violet, purple, or blue cloud which was seen after II and which persisted for some minutes after that time (Several correspondents have described this cloud as if it were the *meteor* itself, and it is necessary to read their reports carefully in order not to confuse the rapidly moving *meteor* with the slow-drifting cloud (A))

(B), (C), the reddish, brownish, or clay-colored clouds seen after II near to and below the cloud (A)

In order to obtain data for a first approximation, I have made brief abstracts of the most important reports, as follows In Section II (only) the italics are usually mine The reports are arranged alphabetically by towns

The accompanying map shows graphically the results of some of the observations It is a first attempt to decide the direction in which the meteor *fell* The point of explosion of the meteor is to be fixed by the observations made at the Lick Observatory, combined with those at the Chabot Observatory, those at Carson, Palo Alto, College Park, and elsewhere

The lines on the map represent the directions in which the meteor lay when its path met the horizon, deduced from the verbal descriptions These lines are often erroneous on account of ambiguities in the accounts

There are seven points designated by letters on the map, namely, A, B, U, W, X, Y, Z

A is the point in whose zenith the meteor exploded, about 28 miles above the earth's surface

B is a point indicated by some reports for the fall of the meteor.

U and Y represent trials which have been made of various hypotheses, and may be dismissed with a word. The meteor would have exploded in the zenith of Y if the sound of the explosion had traveled at about 1,088 feet per second. The meteor would have exploded in the zenith of U if the observations of the Chabot Observatory, combined with our own, had been absolutely exact. As a matter of fact, U is a close approximation to the correct point A, and the latter has been determined by shifting U along the line determined by the Lick Observatory observations unchanged until it harmonized best with the determinations at Chabot Observatory, Carson Observatory, and the observations of Messrs. JOHNSON, STONEROAD, SANDERS, and O'BRIEN at Merced, of Mrs. OSBORN at Atwater, and of Messrs. WEBSTER and MINTURN at Minturn.

The map was constructed chiefly for the purpose of fixing the direction in which the meteor *fell* to the earth, as the place of its explosion (A) was otherwise well determined. For this purpose all the reports were carefully read. The best of them indicate that the fall was almost vertical, but many others gave inclined paths. A black line on the map (when it is unbroken) signifies that a report was at hand which declared the meteor to have fallen in the direction of this line. The lines seem to cluster about four points X, Z, W, B. W appears to be strongly indicated. Many other reports, which need not be specified here, agreed very well in saying that the meteor disappeared at a point about 8 miles above the place W. The observations at Merced, above mentioned, and those at Minturn, and especially the report of Professor FRIEND from Carson (not received till October 12), conclusively prove that the meteor could not possibly have fallen above W, or near it. We may regard the evidence in favor of W as an instructive example of the errors which creep into such observations as those of a rapidly moving and unexpected meteor. The observations of the lowest part of the path of this meteor are particularly unsatisfactory, as has been said, because the attention of all observers was riveted on the splendid cloud which appeared at or near the point of explosion, and especially because the meteor actually divided into (at least) two parts

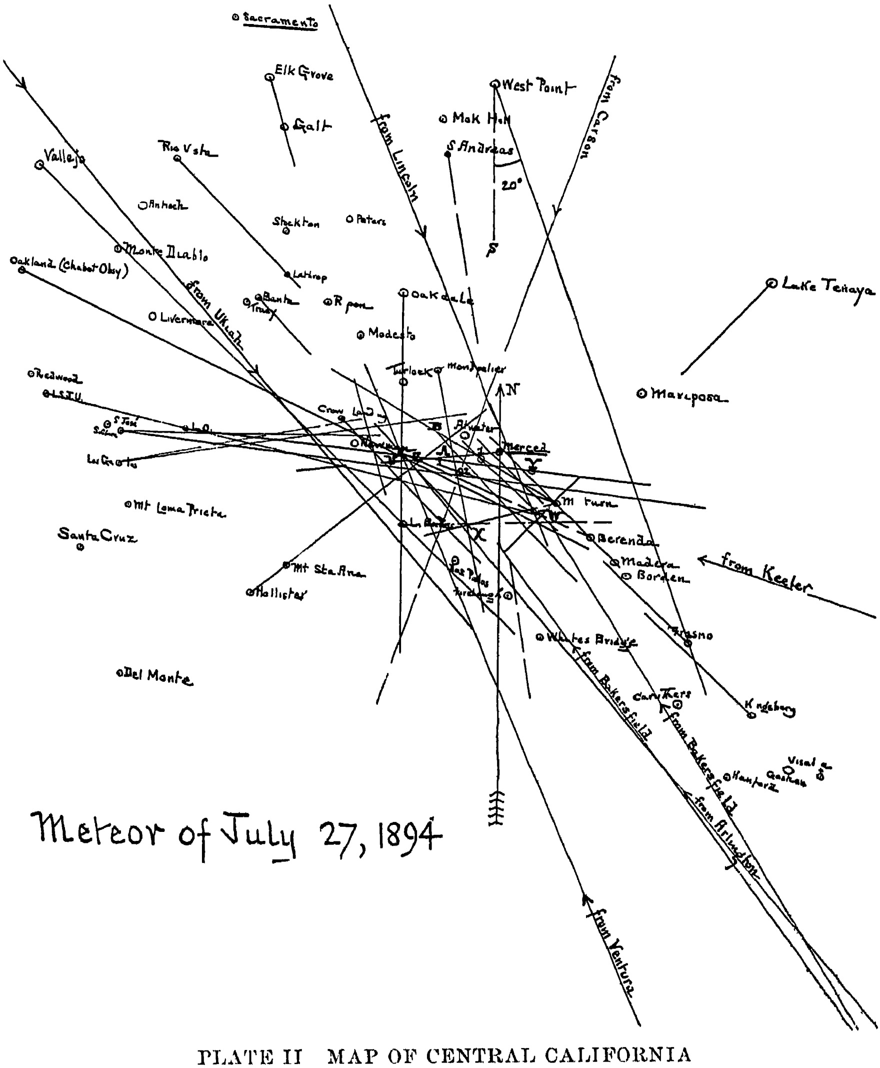

PLATE II MAP OF CENTRAL CALIFORNIA

(The scale is about forty miles to the inch)

towards the end of its course, so that the observations refer sometimes to one of these parts, sometimes to the other

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SECTION II

ABSTRACTS OF SOME OF THE MOST IMPORTANT REPORTS

[The following reports are arranged alphabetically by towns The notes in square brackets are my own A usually refers, in this section, to the point where the meteor exploded, *i e* to a point 28 miles above the point A on the map]

Atwater, Cal Mrs E B OSBORN

The meteor itself was not seen The cloud (A) was about 10° a very little W of S of the zenith

[The meteor at explosion (II) over the point A would have been at an altitude of about 78° and bearing about S W The cloud drifted considerably]

Bakersfield, Cal Mr J B HEWITT (through Hon R THOMPSON)

"My first observation was when the meteor seemed to come in contact with our atmosphere, or show any light It was between the first and second star of the handle of the Great Dipper, this point being nearly 35° to 40° W of N From this point it descended to a point somewhere near 25° to 30° above the horizon, where it exploded, * * * after which it descended behind some trees, * * * the course being some 5° or 7° nearer the N than when first observed by me" No noise was heard "Its general course from here was nearly N W" "The color of the smoke was of a bright whitish cast, and so remained"

A second letter from Mr HEWITT confirms his first, and says that "the Dipper was at that time visible to the eye, or at least before the smoke or vapor left by the meteor in its descent entirely disappeared from view" It was very faint when first seen

[The point in the handle of the Dipper described by Mr HEWITT had an altitude of about 61° at $7^h 30^m$ P s t, and if the meteor were vertically over A on the map the height above the earth would have been over 290 miles The altitude of A from Bakersfield was about 10°, considerably less, that is, than the estimate The meteor was 5° or so nearer the north at its fall than at explosion This observation of the fall points in the direction of W]

Berenda, Cal S P Co 's Agent

"The meteor first appeared about W N W from here, and about 45° above the horizon *It seemed to move about S in falling*"

[If A is the point where the meteor exploded, the Berenda observation agrees well, except that for 45° we should read about 38° The meteor moved *south* in falling]

Borden, Cal S P Co 's Agent

"The meteor was seen W of N W from here, apparently falling almost perpendicularly Disappeared about 20° above horizon"

[The altitude of A was about 30°, of the point where the meteor disappeared, about 6°]

Camp Arlington, Riverside County, Cal Voluntary Observer of the U S Weather Service

The bearing was N 37° 55′ W (true bearing) [This bearing points exactly to U]

Carson City, Nev Chas W Friend, of Carson Observatory

Carson City, October 10, 1894

Prof E S Holden

My Dear Sir Herewith please find memoranda of July meteor as taken from landmarks from observations at the time by Mr Chas Stewart The measurements were made by Mr Kirk (Engineer of the V and T R R) and myself, with transit and tape The transit pier of my observatory was used as a starting point, its position being Long 119° 45′ 42″ 9, Lat 39° 09′ 47″ 2 (authority U S Coast and Geodetic Survey), and altitude above sea-level 4,660 feet The place of observation by Mr Stewart was 323 08 feet north, and 727 2 feet west of transit pier of observatory From this point the meteor was 18° 52′ west of south (true), and burst at an elevation of 7° 03′ The course of meteor was perpendicular Hoping the above information will be of service to you, I remain

Yours sincerely

Chas W Friend

[The altitude of A is 11° Professor Friend has re-examined the landmarks, and considers his measures above to be correct, as they undoubtedly are, from the data]

College Park (University of the Pacific) Professor Robert G Aitken (Observations by Mrs Aitken also)

The meteor *appeared* at an altitude of 25° and azimuth of 270° (east point) It *disappeared* at an altitude of 5° and azimuth of 276° (6° S of E) It took nearly 4 seconds to traverse this path

[A is about 22° altitude as seen from College Park The difference of Prof Aitken's two azimuths is 6°, the later one being most southerly He informs me that the later azimuth is also the best determined The actual velocity of the meteor was about 5 7 miles per 1s If the fall of the meteor were vertical at A on the map, and if it *disappeared* at an altitude of 5°, its height above the earth at disappearance was about 6 miles

The meteor was following and overtaking the earth in its orbit, and the meteor's velocity relative to the earth should be greater than as given by the above estimate]

Crow's Landing, Cal S P Co 's Agent

"The meteor *fell* S E from here" A sound was heard about 3 minutes later

Crow's Landing, Cal Mr C Abad Whitmere (through Hon R Thompson)

The meteor fell perpendicularly, and fell to the earth a little south of east of here "It passed south [of ?] east of this place about 5°, I should judge"

Fresno, Cal Mr A M Drew (through Hon R Thompson)

Mr Drew saw the whole phenomenon The meteor first appeared "about 15° N W of the zenith, and fell toward the N W until it reached a point about 30° from the zenith From that point its course was perpendicular through about 20°" It exploded at this latter point "It was visible between 3 and 4 seconds, as I noted the time particularly"

[If the meteor were vertically over A on the map, its height above the earth at the first appearance would have been over 220 miles]

Fresno, Cal S P Co 's Agent

"Meteor seen from here in northwesterly direction"

Fresno, Cal (Newspaper report)

"When 5° or 6° from the horizon, it exploded"

[The altitude at A was about 23°]

Hollister, Cal (Newspaper report)

It disappeared behind Santa Ana peak

[The peak subtends a vertical angle of about 5°–6° at Hollister The peak is sharp, and the azimuth is, therefore, pretty well determined The line from Hollister to the point of fall passes to the north of A on the map]

Lake Tenaya, 16 miles east of Yo Semite Mr FELIX DEUTSCH

He was facing the west, the meteor fell from a point "somewhat west of the zenith, and a trifle to the south" "The point of its fall was S W of us"

Los Banos, Cal S P Co 's Agent

It shot "in a straight line from N E to S W"

The direction of the path was nearly perpendicular, a little north of east It was fully five minutes later that the report was heard

[This would agree better with A on the map if we read "a little east of north"]

Lincoln, Placer County, Cal Rev E D HALE

He saw the whole phenomenon, and says "if the course of the meteor had continued to the horizon it would have intersected the horizon very near the S S E point It disappeared, however, at an altitude of 20° to 25°"

[A is at an altitude of about 13° from Lincoln The line towards the place of fall points to W]

Livermore, Cal (Press report)

Its fall was vertical

Los Gatos, Cal Reported by Mr GEORGE BRAY

A friend of Mr BRAY's made permanent marks on a tank-frame, which enabled Mr BRAY to give the following data (The observation was made at the S E corner of the N W ¼ of Sec 22, T 8 S, R 1 W, M D B and M) The true bearing from point of observation to point of explosion is N 78° E The altitude of the point of explosion is 30° The angle made by the meteor's path with the vertical (through the point of explosion) was 18° The actual path of the body inclined towards the north A diagram is given, which is here omitted

[The altitude of A was about 22° The line N 78° E is 10° too large to pass through A on the map The inclined path of the meteor would have brought it to earth at a point about 22 9 miles from Los Baños and 15 3 miles from Merced—to the north of A, therefore]

Madera, Cal S P Co 's Agent

The meteor, as seen from here, was very high and almost northwest Its course was indicated by the streak of blue smoke, *was slanting towards the north*

Mariposa, Cal (Press report)

When first observed, it was at an altitude of 85°, and when it fell it ranged southerly, and exploded when it was 15° above the horizon "Just at the point where the explosion took place," the clouds B and C were seen The noise was heard 5 minutes later

[The altitude at A was about 31°]

Merced, Cal (near Merced), at the N E corner of Sec 4, T 8 S, R 13 E Mr W B JOHNSON (his station is marked 1 on the map)

Mr JOHNSON sent on July 31 a very full account of the meteor, with drawings of the cloud A, etc The interval of time between the flash (II) and the report was about 2½ minutes The explosion (II) occurred about 5° S and W of his zenith On September 2, replying to a letter of mine, Mr JOHNSON gives details regarding the position of the meteor at explosion All observers agree that the meteor passed far to the *west* of Merced At Mr JOHNSON'S house the smoke-wreath (A) was west and south, and so "nearly overhead that to observe it with an opera-glass I had to carry out a settee and take a reclining position The altitude of *Alpha Corona Borealis* at the time of explosion may be taken as fixing the angle of elevation of the center of the smoke-mass *very accurately* The only possible error is that I may have over-estimated the amount of the earth's rotation between the time of the explosion and the time when darkness made the stars visible" *Arcturus* "became visible directly *south* of the cloud (A) while the cloud was yet plainly in sight"

Mr JOHNSON incloses two diagrams showing the relation of the smoke-wreath (A) to the stars I understand that the place of the cloud A was fixed in the sky by memory, and that when the stars became visible somewhat later, an allowance was made for the presumed amount of their motion westwards, and that the diagram places the stars where they would have been with reference to the cloud A, had both been seen at the same time There is naturally some uncertainty in this process, but Mr JOHNSON'S observations are obviously very carefully and intelligently made

[The altitude of *Alpha Corona Borealis* at 7h 30m P s t was about 78° at Merced]

Mr JOHNSON says, "*First View* A cloud (A) extending N E and S E" The altitude of A on the map from Mr JOHNSON'S station was about 72°, which agrees well with his estimate Unfortunately, no careful observations were made by observers in this vicinity of the *direction* in which the meteor fell

Merced, Cal Dr E S O'BRIEN

Dr and Mrs O'BRIEN saw the whole phenomenon At the beginning they were facing the west, and the meteor came into view almost directly overhead * A few seconds *before* the explosion (II) it appeared as a ball of light "approaching from a direction a little south of west" A hissing sound was now heard "Then in a few seconds came the great flash of light and the explosion" (II) "The latter was accompanied by a low rumbling sound, as of distant thunder" "This rumbling sound lasted for 30 seconds" The explosion produced smoke, which, at first, assumed a cloud-like body, after which it formed into a large ring, and then gradually twisted upon itself, and broke into a long rope-shape, and as it raised upward with the upper currents of the air, gradually disappeared after 30 minutes This cloud of smoke (A) was quite clear, and showed the effects of illumination by the sun's rays Two smaller clouds (B and C) given off by the explosion, were of a dull red color

[These observations give no data for determining the motion of the meteor On the other hand, the description of the clouds A, B, and C is complete]

Merced, Cal Mr —— STONEROAD, County Surveyor (Through Mr W B JOHNSON)

He observed the cloud (A) from a point 400 feet S of the N E corner of Sec 25, T 7 S, R 13 E He sat on a bench, and saw the cloud just above a banner

*The altitude of the radiant point at Merced was, in fact, about 55°

suspended across the street Subsequent measures (without instruments) by Mr STONEROAD and Mr JOHNSON fixed the altitude of the cloud as from 50° to 60°, and the direction about S 85° W

[The altitude of A is about 66° The azimuth of A is almost exactly as above]

(Near) **Merced, Cal** Mr —— SANDERS (Through Mr W B JOHNSON)

At S W corner of Sec 11, T 8 S , R 3 E , he saw the explosion due W from him, at a point estimated by Mr JOHNSON as 8° from the zenith, or altitude 81°

[His station is marked 2 on the map]

[A is 80° above this station, but lies nearly N W of it]

Minturn, Cal Mr FRANK H WEBSTER, Sunset Vineyard, Sec 24, T 9 S, R 15 E

He was sitting on a north porch facing N W , and saw the whole phenomenon The meteor appeared at an altitude of 80° in the direction N W by W , it attained its utmost brilliancy at 65°, it disappeared at 45° "Had it continued its course to the horizon it would have landed due N W from here At least 3 minutes later the sound was heard "

[A has an altitude of 48° from Minturn, which agrees well with 45° as above The first appearance of the meteor (at 80°) would have been some 124 miles above the earth's surface It moved northerly in falling, say 11° in azimuth The line of its fall is marked on the map 11° north of the line joining Minturn to A]

Minturn, Cal Mr T R MINTURN

He saw the whole phenomenon from the S W corner of S W ¼ of N E ¼ of Sec 13, T 9 S , R 15 E (about a mile N W of Minturn) "The fall was not by any means vertical " The meteor's bearing at the point where its path met the horizon was fixed by a row of orchard trees It was a very little north of due west (by compass) The variation of the compass being assumed as 16°, the azimuth may be taken as about N 74° W (It will be noticed that the two reports from Minturn do not closely agree) "The meteor flashed at a point considerably S of W " Two sounds of explosion were heard

[A has an altitude of about 48° from Minturn]

The line N 74° W passes nearly through 2 on the map The meteor was moving north in azimuth during its fall

Modesto, Cal Mr E C DOZIER, express agent (through Hon R THOMPSON)

The cloud (A) was seen at an altitude of about 45° immediately after the explosion The direction from Modesto was southeast

[The altitude of A is 41°]

Mokelumne Hill, Calaveras County, Cal Voluntary Observer U S Weather Service

"A meteor appeared * * * and burst * * * at an altitude of about 40° * * * "

[The altitude of A is about 21°]

Mount Hamilton (Lick Observatory) EDWARD S HOLDEN

The explosion of the meteor was very near to the time $7^h 30^m$ At $7^h 35^m$ the altitude of the top of cloud A was 26° 57′, and its azimuth S 83° 04′ E The meteor descended from its point of first appearance towards a point whose azimuth was about 88°, that is, it inclined to the *north* in falling, according to my estimates, which were made by comparing the direction of its fall with the side of a window frame

Mount Hamilton (Lick Observatory) J M SCHAEBERLE

The time of hearing the explosion was noted as $7^h\ 36^m\ 15^s \pm 3^s$ Various drawings were made of the cloud—for which see his report in Section VI

Mount Hamilton (Lick Observatory) E E BARNARD

Professor BARNARD's observations are given in full in the *Astronomical Journal*, No 328

The sound was heard by him at $7^h\ 36^m\ 13^s \pm 15^s$ P s t A series of pointings on the densest part of the cloud was made with the finder of the XII-inch Equatorial The first pointing was ten minutes after the explosion

These pointings were—

L O Sidereal Time	R A	Declination
$15^h\ 57^m$	$20^h\ 16^m\ 9$	$+\ 11°\ 8$
16 0	20 15 9	12 3
16 3	20 13 9	12 9
16 7	20 10 5	13 3
16 10 5	20 5 4	14 0
16 14 5	20 1 4	$+\ 15\ 2$

The first pointing gives, approximately, $7^h\ 40^m$ P s t Altitude $= 26°\ 9$, azimuth, S 84° 4 E At $7^h\ 40^m$ the cloud was in the shape of an _| The left hand arm was 2° long The other arm was vertical, and about 1½° long (These estimates are from Professor SCHAEBERLE's drawings) The densest (brightest) part was at the left hand end of the horizontal arm, and Professor BARNARD informs me that all his pointings were made on that part Hence they cannot be used to determine the place of the meteor at the time of explosion, $7^h\ 30^m$ At any rate the cloud had moved considerably by $7^h\ 40^m$, the time of the first pointing

The last pointing was at $7^h\ 58^m$ P s t, and the altitude was about 35° 5 at this time The cloud was changing in shape constantly The altitudes and azimuths of E S HOLDEN and of Mr CAMPBELL refer to the *top* of the cloud, very near where the explosion occurred, and they were made about $7^h\ 35^m$ and $7^h\ 32^m$, respectively

Mount Hamilton (Lick Observatory) W W CAMPBELL

At $7^h\ 36^m\ 14^s$ P s t, two reports of the explosion were heard A very short time after $7^h\ 32^m$ the altitude and azimuth of the upper end of the cloud A were fixed, by reference to *Altair*, as 27° and S 84¾° E, respectively

Mount Hamilton (Lick Observatory) R H TUCKER, JR

He heard two reports of the explosion (the second the louder) at $7^h\ 36^m\ 18^s \pm 3^s$ The trail was seen 4½ minutes before this time The brightest part of the trail was some 3° or 4° long Above it, a very faint line extended from 12° to 16° farther The plane of the whole trail was nearly vertical, but a little south of the vertical plane

Mount Hamilton (Lick Observatory) C D PERRINE

The time of the explosion (II) was $7^h\ 36^m\ 11^s \pm 5^s$

Mount Hamilton (Lick Observatory) A F POOLE

The meteor was first seen (I) about 1½ seconds before it burst (II) at $7^h\ 29^m\ 45^s \pm 10^s$ P s t The plane of the path inclined *south* of the vertical some 5° or 8°

Mount Hamilton (Lick Observatory) Summary of results

The time of first appearance of the meteor is—

I (A F POOLE), about $7^h\ 29^m\ 43^s\,5 \pm 10^s$

The time of explosion is—

II (A F POOLE), $7^h\ 29^m\ 44^s \pm 10^s$

II (E S HOLDEN), not far from $7^h\ 30^m$ —

The time of hearing the reports is—

IV (C D PERRINE), $7^h\ 36^m\ 11^s \pm 5^s$

IV (E E BARNARD), $7^h\ 36^m\ 13^s \pm 15^s$

IV (W W CAMPBELL), $7^h\ 36^m\ 14^s$

IV (J M SCHAEBERLE), $7^h\ 36^m\ 15^s \pm 3^s$

IV (R H TUCKER), $7^h\ 36^m\ 18^s \pm 3^s$

The simple mean of these is adopted as follows—

IV (Lick Observatory, 5 observers), $7^h\ 36^m\ 14^s 2$

IV — II = $6^m\ 30^s 7$, or $390^s 7$

If we knew the mean temperature of the air through which the sound came we could at once fix the distance of the meteor, at explosion, from Mount Hamilton If the temperature were 32° Fahr this distance would be 80 47 miles, if it were — 270° Fahr the distance would be 49 95 miles The distance to the point of explosion (above A on the map) is, in fact, about 59 3 miles, and hence the mean temperature of the air through which the sound moved must have been — 193° Fahr, and the velocity of sound about 800 feet per second, according to the formula given in Section I.

The altitude and azimuth of the top of cloud A are At $7^h\ 35^m$, E S HOLDEN, Alt = 26° 57′, Az = S 83° 04′ E At $7^h\ 32^m$, W W CAMPBELL, Alt = 27°, Az = S 84¾° E At $7^h\ 40^m$, Prof BARNARD noted the first of a series of pointings on the densest part of the cloud (A) left by the meteor, as Alt = 26° 9, Az = S 84° 4 E At $7^h\ 58^m$ the altitude of A was about 35° 5

We may adopt as the place of the top of the cloud at $7^h\ 33^m$ (and this is very near the position of the meteor when it exploded) Altitude = 27°, Azimuth = S 84° E

The direction of the meteor path in its fall was, according to E S HOLDEN, inclining some 5° north of the vertical plane, according to Mr R H TUCKER, nearly vertical, but inclining somewhat to the south, according to Mr A F POOLE, inclining some 5° or 8° south of a vertical See also the reports of College Park (Prof AITKEN), San José (Mr HERRING), San José (Mr HERROLD)

Oakland (Chabot Observatory) Mr CHARLES BURCKHALTER, Director

"The position of the observatory is, Longitude 122° 16′ 39″, Latitude + 37° 48′ The meteor fell vertically downwards in a plane 25° 40′ ± 30′ S of E"

[The above observation was not made by Mr BURCKHALTER, but reported to him by Mr GEORGE CARLTON The altitude of A, on the map, by construction, is about 15½°, which corresponds to an hour-angle of about $4^h\ 7^m$ E, and declination — 10° In October, Mr CARLTON again pointed out to Mr BURCKHALTER the place where the meteor burst, (A), and the latter fixed its position as $t = 4^h\ 19^m$ E, declination — 14° The difference seems large, but I think it is no more than may be expected Mr BURCKHALTER describes the observation as "rough" It is probable that the ± 30′ of the first communication represents too great an accuracy Mr CARLTON says (October) that the meteor burst far "below where the puff of smoke appeared" It is, however, certain that the cloud A was produced by the explosion and appeared at the same altitude The meteor *disappeared* below this point. It was probably dissipated]

Palermo (not on the map) (Newspaper report)

It "appeared in the southern sky, moving in a westerly direction It broke and disappeared a little E of S"

Palo Alto (Stanford University) President JORDAN and Professor HUSSEY

Dr JORDAN writes that the meteor "appeared to fall" in a line joining Palo Alto with a (described) point in the mountains just north of Mount Hamilton Professor HUSSEY has kindly made measures which fix the azimuth of the point On the map the line joins Palo Alto (L S J U) with W The altitude of the mountain *Copernicus*, 4,380 feet high, near Lick Observatory, from Palo Alto is 47′ Mount Hamilton and its neighboring peaks are in plain sight from Palo Alto, and it is certain that no other peaks could be mistaken for them It is also certain that the path of the main body of the meteor was considerably to the *north* of the line Palo Alto to W

The meteor disappeared considerably over the top of the crests

The drawing of Mr ST JOHN, of Oakland, referred to in Section VI, shows that towards the lower end of its fall the meteor divided into two parts One part fell vertically, or nearly so, the other flew off in a zigzag line towards the south It is my opinion that this latter fragment (which was quite bright) was observed at Palo Alto and at College Park and also by Messrs TUCKER and POOLE at Mount Hamilton The azimuth of the lower end of the meteor's path would thus be placed too far *south* I know of no other way of reconciling these careful observations

Riverside, Cal (not on the map, it is near Arlington) (Newspaper report)

It descended perpendicularly and exploded some distance above the horizon

San Andreas, Cal (Press report)

Its fall was almost vertical

San Jose, Cal Mr C D HERROLD

Its altitude was 28° It was close to the equator, "inclining downward slightly towards the north"

San Jose, Cal Mr and Mrs S H HERRING, No 12 Pleasant Ave

Mr HERRING says "its first appearance was not very bright" (I), "but it rapidly increased in brilliancy and showed several colors when it burst" (II)—"blue, red, and yellow, with intermediate or blending tints" The direction of its *fall* was "very nearly due east, slightly *south* of east Its fall was nearly perpendicular from our point of view, just slightly bearing to the *north* in its fall" The altitude at the time of explosion was estimated at 30° The explosion shattered the meteor into pieces—"not less than three pieces, nor more than four"—and they were not far separated in falling They "fell straight down, with little divergence" "This latter fall I saw distinctly, and both Mrs HERRING and myself accurately agree in all we both saw"

San Andreas, Cal (Press report)

The meteor descended almost vertically It fell a very little east of south

Santa Clara, Cal Mr GEORGE BRAY

Mr BRAY saw the whole phenomenon The meteor first appeared at a faint point of light, and gradually increased in size till it exploded Its track was perpendicular—vertical The cloud (A) drifted towards the north The altitude of the point of explosion was 30° The interval of time between the flash and the report was 7¼ minutes The azimuth (by compass) was observed to be N 70° E, or the true bearing N 86° E

[This refers to a *vertical* fall, as reported by Mr BRAY See, however, *Los Gatos* observations, also reported by Mr BRAY The altitude of A is about 22°]

Tracy, Cal (Press report)

It fell from an altitude of 60° to near the horizon At 30° it left a cloud behind it, etc (A) Five minutes later a report was heard

[The altitude of A was 26° An altitude of 60° corresponds to a height above A of some 89 miles]

Vallejo, Cal Hon R Thompson

San Francisco, Sept 10, 1894

Prof E S Holden, *Mount Hamilton, Santa Clara Co, Cala*

My Dear Sir On the 27th of July, 1894, at about 7 30 P M, I observed the fall of the meteor of which I wrote you I was standing upon a hill on which the Orphans' Home is situated, at Vallejo, Solano County, Cal, looking over the farms southeasterly from where I was standing There were no trees to intercept my view, and the horizon was about 4 miles to the southeast I was looking into the valley when I saw the first gleam of light made by the meteor As near as I could judge, it first appeared about 32° above the horizon as a white light It fell directly towards the earth in a perpendicular line, this attracted my attention, as I had never seen one fall so vertically before It increased in intensity of light, and appeared to be nearer as the white light became more and more intense—it not only increased in intensity but in size to a perceptible extent for about one third of its entire passage, when it appeared to explode At the time it exploded, or seemed to, it had the appearance of an immense rocket about a half mile away None but white light appeared until it broke, but after that there were many tints About one third of the way from the western side, or edge, there was a dark bluish-brown line, on the westerly side of this streak there was a definite dark edge, but on the eastern side it ran into red and yellowish The other parts of the meteor after it broke showed a variety of colors It was so far distant that the colors blended one with another so I could not see any part falling independently from the whole The outer parts faded just as a rocket generally does and at last there was only one line of light passing on That one line did not go far until it seemed to me to become disintegrated before it reached the earth I subsequently examined the location and found that it disappeared below the horizon It seemed to fall, or, if it had reached the ground where it appeared to me to be, it would have done so at a point a little to the right of a farm house with a square roof, and about 2° northeasterly of Mount Diablo I subsequently used a compass and found the course, by compass, exactly S E and N W, so the course of the meteor must have been, by compass, due northwest As it fell its motion was perceptibly retarded all the way down After observing its fall to the end, I raised my eyes, and in the upper part of the path I saw a long grayish-white line of what appeared to be a cloud or smoke It was perfectly straight, and appeared of about an even thickness In about 5 to 7 minutes the center began to curve to the east I observed it only about 10 minutes I timed the fall subsequently, by counting, and estimated it from 4 to 5 seconds—I think nearer 5 than 4 The line of vapor left was from near the meteor's contact with the atmosphere and just after it went to pieces It extended just about one third of the whole journey of the meteor through the atmosphere of the earth

I am interested to find out many things about that July meteor I endeavored to find where it first came in contact with our atmosphere, what angle it made through it, how far it went after coming into the earth's atmosphere, where it broke in pieces, where it struck the earth, if it did so, and how many degrees of heat it generated, also, the report, if any, it made Of course, my conclusions would be likely to be unreliable, so I concluded on the start to send all information to you I am of the opinion that, as to the time of falling, the letter from Tracy is the most reliable, and also as to the time the explosion was heard after it occurred

You will find that the letter from Crow's Landing tells, I think quite accurately, as to how far north it traveled It would seem that it fell due east

from the Observatory It was heard in Stockton, as well as in places nearer its fall, but the time was more closely noted at Tracy than elsewhere, as it appears from the letters The time after explosion will give the distance it was from Tracy at the time of the explosion As I concluded it was moving in nearly the same direction of the earth around the sun, so the motion of the earth would diminish the speed through our atmosphere, not increase it If it fell 150 miles through our atmosphere in 4 seconds, it might not be difficult to find the speed of the meteor through space You will know as to whether the information you have, will give you all the different things I would like to know as to that meteor I send you ten letters, and if I get others I will send them also You can keep them, as my only aim is to preserve as many facts about the meteor as possible

Yours,

R THOMPSON

[Its first appearance was 32° above the horizon, which corresponds to about 59 miles above the point A on the map It exploded at about $30° - 11° = 19°$ in altitude The altitude of A is about 15° In platting the direction I have used the bearing referred to Mount Diablo The time required for the fall agrees closely with the estimates of Professor AITKEN (College Park) and of Mr DREW (Fresno), and must be very close to the truth]

Wawona, Cal Mrs A H WASHBURN

The meteor fell "from the southwestern sky "

[U]

Webber Lake, Cal Mr T ELLARD BEANS

Webber Lake is 25 miles N W of Truckee, in Sierra County, and is about 7,000 feet above the sea

It appeared to descend perpendicularly, inclining slightly towards the east It exploded "just before it reached the water "

West Oakland, Cal Report of Mr CHAUNCEY M ST JOHN, of San Francisco

"About 7 35 P M on the 27th day of July, 1894, my attention was attracted to the heavens above the eastern horizon by a meteor It was seen by me from West Oakland, on the edge of the bay I have seen many shooting stars and meteors before, but never such a wonderful sight as this was I will make a faint attempt to describe this heavenly body, in addition to the accompanying water color sketch, which is about as near perfect, I think, as could be made from memory Measured by the arc of a vertical circle, the meteor was apparently (explosion) above the horizon about 50° The meteor's path was about E by N true, the upper portion of its trail (above explosion) as well as lower (below explosion) could be seen distinctly for twenty minutes after the meteor had disappeared At the point of explosion there was a number of small smoking particles that seemed to burn and dart in every direction, and only one (outside of the main body, which continued on its course, but falling with less rapidity after the explosion) was seen to break away in a southwesterly direction, leaving a trail of smoke behind You will please notice in the water-color, on the right, its appearance drifting through space in a zigzag manner, the smoke rolling off the outer edge, resembling very much in formation water flowing over the pipe of an artesian well

"The smoke or gas remaining in the main trail had the appearance of smoke shooting in the air from a locomotive when hauling a heavy freight train up a grade On account of the meteor's great height, there must have been a small current of atmosphere, for the smoke remained for quite a time in perfect shape It had a distinct rotary motion Fortunately I was look-

ing in the direction of the meteor, and saw the object some time before I heard the explosion "

West Point, Calaveras County, Cal Rev W P S DUNCAN

"I saw the meteor fall from first to last" When first seen the meteor was about 35° above the horizon due south Its track appeared to make an angle of about 60° measured from an east and west line It seemed to fall at a point about 20° E of S (magnetic)

[Magnetic south is S 16° W Hence it *fell* S 4° E It ranged E in azimuth in falling, apparently]

Yuba City, Cal (Press report)

It dropped "swiftly from the sky in a slanting direction, southeasterly from Yuba City "

SECTION III

DETERMINATION OF THE PLACE WHERE THE METEOR EXPLODED

It is remarkable that among so many intelligent observers, there were so few accurate observations of the time at which the meteor exploded, or of the time when the sound of the explosion was heard

The observations are too often not clear in describing the direction of motion of the meteor in its fall, so that it is sometimes quite difficult to decide whether a report relates to the meteor when it was high up in the heavens, or to its position as it approached the horizon

As I have said, there are especial reasons in the case of this meteor for the lacks referred to, because the violet cloud which was left behind was so strange and beautiful as to command one's whole attention, and because of the separation of the meteor into two parts We have many reports relating to this cloud which describe it most accurately, and three observers—Mr JOHNSON of Merced, Mr STEWART of Visalia, and Professor SCHAEBERLE of Mount Hamilton—have given careful drawings of it, taken at short intervals These and other reports relating to the cloud are all that could be desired

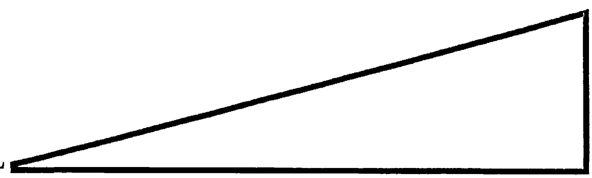
The drawing by Mr ST JOHN of the general aspect of the meteor (see frontispiece) is very satisfactory and beautiful

The meteor was accurately observed at Mount Hamilton by seven persons The time of explosion (II) is fixed by two observers, the time of the arrival of the sound (IV) by five, the altitude and azimuth of the cloud by three, etc All these

2

observations are consistent The time required for the sound of the explosion to reach us was $6^{m}\ 30^{s}\ 7$ If we know the velocity at which the sound traveled, a simple multiplication will give the corresponding distance We know that the velocity of sound varies with the temperature—sound travels slower at a low temperature,—and that it varies with the initial intensity of the sound—very intense sounds travel faster than less intense ones

We do not know the velocity of sound in the case before us Let us assume, for a first trial, that the average temperature of the air was 32° Fahr (which is evidently too high), and see to what conclusions this leads The velocity will then be 1,088 feet per second, or say 12 4 miles per minute, the time of transmission was 6 5 minutes, and the distance of the meteor in a straight line was $80\frac{1}{2}$ miles, on this hypothesis



If we imagine a horizontal plane through the summit of Mount Hamilton (4,209 feet above the sea) and if we drop a perpendicular line from the meteor's place when it exploded (II) we shall be able to fix this place by solving the triangle LMK

L is the place of the Lick Observatory, LK is a plane tangent to the earth at L, M is the meteor when it exploded, the distance LM is $80\frac{1}{2}$ miles, the angle at L is 27°, the distance LK is $71\frac{7}{10}$ miles, MK is $36\frac{1}{2}$ miles L is 4,200 feet above the sea, and K is about 6,200 feet higher still The distance of M above the earth's surface is about $38\frac{1}{2}$ miles, and M is in the zenith of a place about 8 miles *east* and 4 miles *south* of Merced This point is marked Y on the accompanying map

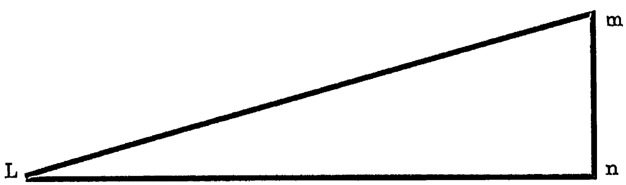
Dr O'Brien, Mr Johnson, Mr Stoneroad, and Mr Sanders, of Merced, are unanimous in saying that the meteor exploded *west* and *south* of Merced, it could not have exploded to the *east* of their stations It follows, therefore, that the velocity of sound assumed above is considerably too great

For a second approximation let us include the observation of Mr Carlton, reported by the Chabot Observatory, who saw the meteor descend vertically in an azimuth E 25° 40′ S

By consulting the map it appears that the distance from the Lick Observatory to the point where the lines from the Lick Observatory and from the Chabot Observatory intersect is about 44 2 miles

In the triangle L*mn*, the angle at L is again 27°, the distance L*n* is about 44 5 miles, the distance L*m* is 49 95 miles, and *mn* is 22 68 miles The velocity of sound would be about 675 feet, and the average temperature about — 270° Fahr

The earth's curvature, together with the height of Mount Hamilton, is a little over 1 mile, so that the point *m* is, say, 23 7 miles above the earth's surface, and in the zenith of a point 44 2 miles from Mount Hamilton in the azimuth S 84° E This place is about 1¼ miles *south* and 21¼ miles *west* of Merced, in Sec 33, T 7 S, R 10 E, and is marked U on the map



On October 12 I received the report of Professor Friend, of the Carson Observatory Mr Stewart, of Carson, saw the meteor fall *vertically* behind a building, and noted its position with respect to chimneys, etc Professor Friend, using Mr Stewart's description, has kindly measured the angles, etc (See his report in Section II) The observations at Mount Hamilton are so full and so consistent that we must conclude the meteor to have fallen along the line S 84° E and to have exploded at an altitude of 27° The point A (of the map) along that line best suits the observations of Carson, Chabot Observatory, Merced, Atwater, and Minturn It is in the zenith of a point about half a mile *south* and half a mile *west* of the N E corner of T 11 E, R 8 S The point of explosion was a trifle over 28 miles above the surface of the earth The point A is adopted as the point in whose zenith the meteor exploded

SECTION IV

DETERMINATION OF THE PLACE WHERE THE METEOR FELL

From the abstracts of reports given in Section II the directions—bearings—in which the meteor's path (prolonged) would have met the horizon can be inferred The (unbroken) lines on the map represent these directions In this section it is assumed that we already know the point where the meteor exploded, namely, 28 miles above A on the map

The platting was done on a tracing made from the excellent map of California issued by the State Mining Bureau in 1891 The scale was 12 miles to the inch The preceding plate is photographically reduced from the tracing

There are four main intersections of the lines drawn, namely, B, X, Z, and W Either one of these will satisfy a number of good observations To decide which one to accept, it is necessary to criticise the reports closely In Section II of this paper I have often marked at the end of a report the point (Z, X, or W) which seems to be indicated by the data there given

According to the preceding reports, the meteor in falling moved *north* to the observers at Bakersfield, Hollister, Los Gatos, Madera, Merced, Minturn (two independent observers), Mount Hamilton (E S H) San José (two observers)

It moved *south* according to Mount Hamilton (R H T and A F P independent observations), and according to the careful observations at College Park Two stations north of Merced, viz , Webber Lake and West Point, report its fall as nearly vertical, but inclining somewhat to the *east*

The following stations report the fall as substantially *vertical*, viz Borden, Carson, Crow's Landing, Fresno, Livermore, Los Baños, Oakland (Chabot Observatory), Riverside, San Andreas, Santa Clara, Vallejo, and Visalia It will be noticed that these stations are distributed in a circle around Merced

A number of observers (as above) do not agree that the meteor's path was vertical At Mount Hamilton I compared the direction of fall with a window frame, and observed that it deviated to the north The observer at Los Gatos referred this direction to fixed marks Hollister saw it dis-

appear behind a sharp peak. Two observers at San José and two at Minturn indicate that it moved north in falling.

On the other hand, two observers at Mount Hamilton (with no fixed marks, however) report its path inclining towards the south. The excellent observations at College Park give 6° for the amount of the southerly inclination. Moreover, the observations at Palo Alto are not to be reconciled with a path to the north of a vertical through A on the map.

Under these circumstances it seems impossible to decide which way the path of the meteor through the atmosphere deviated from a vertical line through A on the map.

It is much to be regretted that the question has to be left in so unsatisfactory a state, but I do not know how to reach any certainty without arbitrarily rejecting observations which are *prima facie* trustworthy. The best possible conclusion seems to be that the fall was, in fact, vertically downwards to the point A.

At the time of the explosion, or rather series of explosions, the meteor must have thrown off many fragments, which would be scattered over a very considerable area. A few of these continued towards the earth, making the bright streaks of the trail.

Height of the Meteor when it Disappeared.—It is certain that the meteor, as a single mass, did not reach the earth. It exploded at a height of some 28 miles and left the clouds (A), (B), (C)—and three or four fragments (see the report of Mr. HERRING, of San José) fell. These falling fragments were consumed or dissipated before they reached the earth, so far as can be judged by the eye, probably at a height of some six miles above the earth's surface. It is not possible to fix the place where they fell. They are probably confined to a roughly circular area having A for center, and ten or twelve miles in diameter. It is likely that the fragments which reached the earth were small, and comparatively few in number. It does not seem likely that a search for them would be rewarded.

Height of the Meteor when it First was Visible.—Several observers saw the meteor a long distance above the point of explosion. The heights vertically above the point A on the map corresponding to the times of first appearance are, approximately—

Bakersfield, 290 miles (estimate probably too large)
Fresno, 220 miles (estimate probably too large)
Minturn, 124 miles (estimate probably too large)
Tracy, 89 miles
Vallejo, 59 miles

The radiant point (R. A. $16^h 0$, Decl. $+31^\circ 5$) had an altitude of about 85° at Mount Hamilton at $7^h 30^m$.

SECTION V.

ORBIT OF THE METEOR OF JULY 27, 1894.

With the data of Sections III and IV, I have calculated the meteor's orbit. As the data are not very precise the radiant point was obtained by construction on a small globe. Its position is

Radiant of Meteor R. A. $16^h 0$, Decl. $+31^\circ 5$;
Long. 225°, Lat. $+51^\circ$.

There is, so far I know, no well-marked radiant in this place.

The elements of the orbit (assumed to be a parabola) are approximately

$$\begin{aligned} \Omega &= 125^\circ, \\ i &= 20^\circ, \\ \pi &= 130^\circ, \\ \log q &= 0.0060, \\ q &= 1.016. \end{aligned}$$

The meteor was then a little nearer the sun than was the earth, near perihelion, moving in an orbit inclined about 20° to the ecliptic.

The assumption that the orbit of the meteor is parabolic refers to one limit (a = infinity). If we assume a to be 2.2 (corresponding to the major axis of the orbit of ENCKE's comet, approximately) we have another limit. In this case we have

$$\Omega = 125^\circ, \quad i = 11^\circ 5, \quad \pi = 13[illegible]$$

TISSERAND's Criterion (V. J. S., vol. 29, p. [illegible]) shows that q must be greater than 0.77.

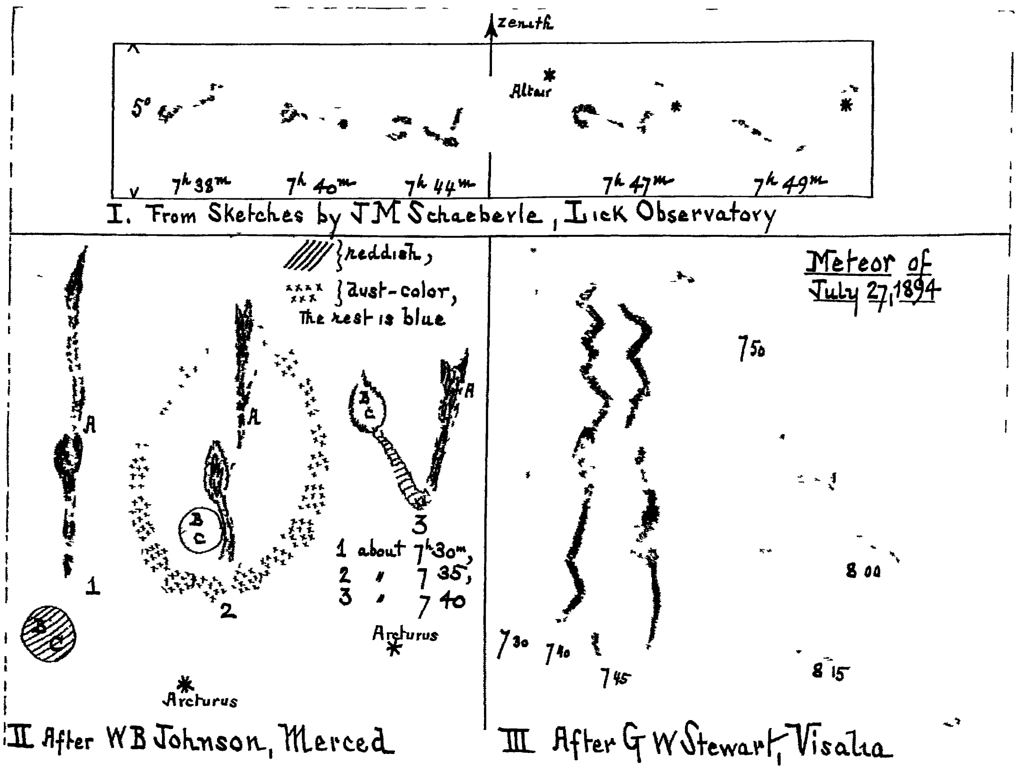


PLATE III DRAWINGS OF THE METEOR OF JULY 27, 1894

SECTION VI

THE LUMINOUS CLOUDS LEFT BY THE METEOR

Sketches of these luminous clouds have been received from Professor SCHAEBERLE (Mount Hamilton), Mr JOHNSON (Merced), Mr STEWART (Visalia), and a diagram from Mrs OSBORN (Atwater) Mr JOHNSON's drawing was in colors The first three are reproduced in the accompanying plate, and their descriptions are to be found in Sections II and VII, respectively

Besides these we have received a beautiful and artistic water-color drawing by Mr CHAUNCEY ST JOHN, which represents the meteor at the instant of explosion in a very faithful manner I much regret that it is not possible to reproduce the water-color in this book One very interesting thing may be noticed in this drawing At the lower end of the meteor's path, just where the path apparently terminates, Mr ST JOHN has drawn a zigzag branch of the trail extending southwards and downwards, which is also described in his report I did not myself notice this branch at Mount Hamilton It is noteworthy, however, that such a branch seen from Santa Clara or Palo Alto might have been observed to fix the azimuth of the point of fall, and that such an observation would have been too far *south* for the general direction of the fall It is my opinion that this fragment of the meteor was observed by the observers just mentioned

The cloud (A) (see the plate)—a large, violet, luminous mass—was noticed by every one In many descriptions it is referred to as "the meteor" It was seen by Professor SCHAEBERLE from $7^h\ 30^m$ to $8^h\ 2^m$, Mr STEWART still saw it at $8^h\ 15^m$

This cloud (A) was undoubtedly composed of particles derived from the explosion of the meteor Its light may have been intrinsic, *i e*, these particles may have been hot and self-luminous, or its light may have been reflected sunlight

The sun set on July 27 about $7^h\ 17^m$, and its rays would still illuminate an object 28 miles high at 8^h

It is not necessary to give any description of the cloud (A) in this place, since the reports of many of the observers describe it accurately A very curious feature was not seen

from Mount Hamilton, namely, the two reddish clouds (B) and (C) They are drawn by Mr JOHNSON and described in the several reports They gradually separated from the cloud (A) and settled towards the earth The suggestion that they were composed of the heavier particles of the products of explosion is, no doubt, a true explanation The different shapes of the cloud (A), as seen from different stations (Mount Hamilton, Merced, Visalia), would enable us to construct its real shape in space, but a determination of this would have only a curious value It was not practicable to determine its spectrum, which would have been an observation of interest

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SECTION VII

REPORTS ON THE METEOR OF JULY 27, 1894

Section II contains *abstracts* of some of the reports on the meteor, particularly of those which are useful in fixing the orbit The present section is devoted to all the reports received at the Observatory They are arranged alphabetically by towns The Index of Names in Section VIII will enable the report of any particular person to be found If the abstract of a report given in Section II is a complete account, the report is not reprinted here

Athlone, Cal S P Co 's Agent

Meteor seemed to start from a point directly overhead, reaching the earth in a southeasterly direction from this place

[Athone is just S of Merced]

Banta, Cal S P Co 's Agent

"It fell S E of here "

Berenda, Cal S P Co 's Agent

The meteor first appeared about W N W from here, and about 45° above the horizon It seemed to move about south in falling

Caruthers, Cal S P Co 's Agent

The observer was facing San Francisco when the meteor came into view on the west side of the railroad line, traveling towards the earth, with a slight slant towards the north and west He followed it to (say) ½° from the horizon, where it exploded, emitting two short streaks of orange-colored light [B and C?] "A line drawn from Caruthers towards the point where it disappeared from view would pass, I think, about 3 miles north of Collis, or about due N W from here "

[The meteor must have exploded at least 20° above the horizon at Caruthers]

Dos Palos, Cal S P Co 's Agent

The meteor "seemed to be nearly overhead" It started "from the S W horizon, taking a course nearly N E" "At a point N E or E N E from here it burst"

[The report is from hearsay]

Elk Grove, Cal (Newspaper report)

The meteor reached the earth in the azimuth Elk Grove-Galt

Farmington, Cal S P Co 's Agent

Fell east of southeast from here

Firebaughs, Cal S P Co 's Agent

He was in a house, seated, facing N W, and saw the meteor through a window It was moving northerly

Fowler, Cal (not on the map) Mr Geo A Leon (through Hon R THOMPSON)

The cloud (A) was seen north of here

Fremontville, Ventura County, Cal Voluntary Observer of the U S Weather Service

The meteor fell in the N N W

Fresno, Cal S P Co 's Agent

Meteor seen from here in northwesterly direction

Keeler, Cal Mr R J LAWS, of Hawthorne, Nevada (through Hon R THOMPSON)

Mr LAWS was at Keeler, looking at the mountains N W of Owens Lake The course of the meteor appeared "a little south of east, with a slight inclination to the east" "It fell a very little north of west from the summit of Mount Whitney"

Keeler, Cal Mr C M RICHARDS (through Hon R THOMPSON)

"The fall was 40° or 45° to the northwest," "north of west"

Keeler, Cal (Newspaper report)

The meteor appeared to shoot up from the cloudless horizon It appeared to be a few degrees north of west, and almost over top of Mount Whitney

Kingsburg, Cal S P Co 's Agent

The meteor fell in the direction of Lathrop

Livingston, Cal S P Co 's Agent

When meteor exploded it was apparently directly overhead (and seemed to be traveling in a westerly direction It did not appear to be descending, but traveling westward at about the same altitude as when first observed)

[I suppose the words inside the ( ) to refer to the cloud, not to the meteor]

Merced, Cal S P Co 's Agent

It was apparently going north

Milton, Cal Observer U S Weather Service

A meteor appeared in the southern sky and burst with quite a report at 7 30 P M of the 27th, leaving a perpendicular trail of smoke or vapor in the previously clear sky, of about 5° in length, at an altitude of about 40° This smoke or vapor kept its serpentine shape for about five minutes and then gradually diffused

Montpellier, Cal S P Co 's Agent

The meteor appeared to be going south of southwest and broke near the horizon towards the Coast Range about on a line from here to Atwater or Livingston

Mount Hamilton Edward S Holden

The following observations of the aerolite of July 27 will furnish accurate determinations of the altitude and azimuth of the point of first appearance of the meteor The times of first appearance, of the arrival of the sound of its explosion, and other physical observations, are given by other observers

I was sitting with my back to a window, reading by the strong twilight, about $7^h 30^m$ The page of my book was suddenly lighted up (by an illumination due to the explosion of the meteor) The glare was strongly yellow I turned and rose from my chair barely in time to see the bright head of the meteor (which appeared to me strongly yellowish white) an instant before it disappeared a few degrees above the horizon* The sky was perfectly clear, though its lower strata were filled with dust particles, which produced a strong absorption Above the head of the meteor was the nearly vertical streak, or trail, left in its passage I looked at my watch shortly after the disappearance of the head of the meteor and noted the time as $7^h 30^m$ P s t As I was too late to record the true time of the explosion, I did not note the seconds The streak or trail left by the meteor was some 20° long I estimated that its direction was not vertical, but that it was inclined north of the vertical some 5° I aided myself in this estimate by the vertical side of the window frame Other observers have, however, recorded that its path was inclined to the south of the vertical some 5° or 8° At $7^h 30^m$ the upper end of the narrow streak which marked the meteor's path was a long, bright violet cloud, perhaps 20′ wide and some 10° long Let us call the upper point of this cloud A (corresponding approximately to the point where the meteor entered the atmosphere of the earth) I fixed the altitude and azimuth of A by moving a table in my study until a line from the corner of the table through the corner of one of the window panes passed through the point A While I was engaged in doing this I heard at least *three* reports of the explosion of the meteor and noted the time (only approximately) as $7^h 36^m 5$ The cloud A changed its shape from a nearly vertical line to that of a reversed L (thus _|) at $7^h 37^m$, and at $7^h 41^m$ there were two bright, large oval knots on the _|, one at the left hand (north) extremity of the lower branch, the other less bright, at the intersection of the two branches The brighter knot was still visible at $7^h 47^m$ The altitude of A was 26° 57′ at about $7^h 35^m$ The azimuth of the east wall of my house is S 12° 29′ E The azimuth of A was S 83° 04′ E at about $7^h 35^m$ These coordinates are probably right to within 30′ or so These figures agree closely with those of Professor Campbell (27° and 84¾°)

The times corresponding to the first appearance of the meteor, and to its explosion are given in the notes of other observers which follow These times, together with the altitude and azimuth of A just determined, completely determine the position of the meteor when it exploded, as seen from Mount Hamilton

Mount Hamilton Prof J M Schaeberle

The noise of the explosion was heard at $7^h 36^m 15^s \pm 3^s$ At first thought it was due to blasting in the neighborhood, and on looking in the direction from which the sound came my attention was attracted to the vividly bright cloud of smoke left by the explosion It had the appearance of being self-luminous, when first seen The main cloud streak was nearly vertical, about 3° long, with a fainter and narrower streak extending downwards nearly to

* About 5° or so

the horizon, then gradually changed into an _| shaped figure, the brightest portion of which was at the lower left hand extremity of the outline The illumination was last seen with certainty at $8^h\ 2^m$, when it was 2° or 3° to the northeast of *Altair*

[The sketches by Professor SCHAEBERLE are copied in the preceding plate]

Mount Hamilton Prof E E BARNARD

[The observations of Professor BARNARD were communicated by him to the *Astronomical Journal*, and are printed in full in No 328 An abstract is given in Section II]

Mount Hamilton W W CAMPBELL

On coming out of one of the residences at $7^h\ 32^m$ my attention was called to a remarkably bright streak in the eastern sky It was light blue in color, and had a metallic luster It was about 8° long, and substantially vertical in direction The upper half was very bright, while the lower half was comparatively faint, with here and there a bright condensation The column did not seem to be moving, vertically, but it gradually became crooked, as if under the action of air currents There were whirls in it, such as one sees in smoke columns At $7^h\ 36^m\ 14^s$ two explosions were heard They were of about equal intensity, probably half a second apart The reports were such as I have often heard when I have been a mile or two from blasting in stone quarries The reports seemed to come from the east

Shortly after the explosion I estimated that the upper end of the bright column was 4° below and 8° north of the first magnitude star *Altair* The altitude of the top of the column was then, therefore, 27°, and the azimuth was S 84¾° E I watched the column until about $7^h\ 45^m$, when it was still plainly visible, though very much distorted and broken up

There is practically no doubt that the phenomena observed were due to the falling of a large meteor, which exploded to the east of Mount Hamilton

Mount Hamilton R H TUCKER, JR.

I heard two reports of the explosion (the second the louder) at $7^h\ 36^m\ 18^s \pm 3^s$ The trail was seen 4½ minutes before this time The brightest part of the trail was some 3° or 4° long Above it a very faint line extended from 12° to 16° farther The plane of the whole trail was nearly vertical, but a little south of the vertical plane

Mount Hamilton C D PERRINE

While sitting in my room in the brick house my attention was attracted by a dull, heavy explosion, followed in a short interval of perhaps half a second by one nearly as heavy as the first Taking out my watch I found the P s t to be $7^h\ 36^m\ 11^s \pm 5^s$.

The sound apparently came from the east, and the building seemed to rattle a little, such as might be expected from a heavy air wave, but I did not notice any shaking of the floor

I had a light burning in my room and therefore did not *see* anything of the meteor, and supposed the noise I heard was due to some other cause until I learned otherwise an hour and a half later

Mount Hamilton A F POOLE

I noticed the light from the meteor about 1½ seconds before it burst The head of the meteor was moving rather slowly, and it came within a few degrees of the horizon and exploded at $7^h\ 29^m\ 45^s \pm 10^s$ P s t The color of the head was greenish The path of the meteor was nearly vertical, the plane of the path was south of the vertical some 5° or 8°

Newcastle, Cal C H KELLOGG

On the 27th, a little after 7 o'clock, a brilliant meteor or ball of fire burst into view about 45° above the western horizon and although the sun had set but a few minutes before, the light of the meteor as it separated into two large balls and exploded, was so dazzling as to blind the eyes for an instant The object appeared to be very near, but no report was heard from the explosion, as it was expected there would be, and was listened for

Oakdale, Cal S P Co 's Agent

It seemed to fall south of here

Raymond, Cal (not on the map) S P Co 's Agent

"The falling meteor appeared almost due west from here It seemed to be traveling *in a southerly direction* "

Rio Vista, Cal Observer U S Weather Service

At 7 30 P M of the 27th, a brilliant meteor was observed almost exactly in the southeast, having a motion from the northwest, leaving a visible train of bluish smoke, which lasted for over 20 minutes Elevation when first observed, about 35°

Ripon, Cal S P Co 's Agent

"The meteor appeared to take a southeasterly course It seemed to explode when near the earth Rumbling noise and report were heard here about 8 minutes after it was seen "

Stockton, Cal J T SUMMERVILLE, Esq , attorney at law (through Hon R THOMPSON)

Mr SUMMERVILLE was driving southward from the S W boundary of Stockton He saw the meteor before explosion, and heard "a sizzling noise" as it descended It then burst and disappeared About 3 or 4 minutes later *three* distinct detonations were heard "The meteor appeared to me as if it were falling in a southeasterly direction, somewhere about French Camp "

[French Camp is about south of the center of Stockton]

Tehachapi, Cal Wells, Fargo & Co 's Agent (through Hon R THOMPSON)

The meteor fell directly N W of us It seemed to be a little north of Bakersfield from here

Tracy, Cal D S TROTH, Wells, Fargo & Co 's Agent (through Hon R THOMPSON)

Meteor was first seen at about 7 28 or 7 30 P M , and the explosion was here about 7 35 or 7 36 P M The sound resembled very much that of blasting at a distance Was traveling a little west of southeast at a very rapid rate of speed, and downward , left light-colored streak behind, which was somewhat lighter than that of ordinary smoke, which was visible for about 25 minutes

Turlock, Cal S P Co 's Agent

Meteor was seen by a number of people about 7 45 P M , July 27th , course, southeast The report from it was heard about 5 minutes after its passage

Turlock, Cal Observer U S Weather Service

About 7 30 P M of the 27th, a very brilliant meteor shot across the sky from northwest to southeast, visible for about 15 to 20 minutes before the smoke from it entirely disappeared

Ukiah, Cal Mr G T RHODES

The whole phenomenon was seen 'A line drawn from Ukiah to Tulare Lake by the map is the direction of its fall from here "

Ventura, Cal Observer U S Weather Service

At 7 15 P M on the 27th, a wonderfully brilliant meteor was seen in the north-northwest, about 10° above the horizon, which left a luminous cloud of changeable form, visible for half an hour

Visalia, Cal G W STEWART [See the plate]

At 7 30 P M * * * "a meteor was observed in a northwesterly direction from Visalia The descent was almost vertical A perpendicular fleecy column, about 15° in length, remained to mark the meteor's path, retaining its original position for nearly 15 minutes The ends were very thin The diameter varied little, except near the center, where an oval-shaped mass of a steel-blue tinge shone brilliantly After 15 minutes the column was reduced in length by the disappearance of each extremity, the upper end began to fall to the westward, and the whole was broken into an angular line In 25 minutes the sharp angles disappeared In 30 minutes the upper end had descended very nearly to a horizontal with the lower end In 35 minutes the cloud was the shape of the upper half of a loop, with the ends larger and more luminous than the center At 8 15 the cloud was barely visible to the naked eye The train drifted very slowly to the westward "

Winnemucca, Nev Bishop H W WARREN

"The line of light inclined slightly to the right from the perpendicular, and went behind the hills about 12° to the right or north of the trend of the track west of Winnemucca " The smoke remained in sight for 15 minutes

SECTION VIII

INDEX OF NAMES

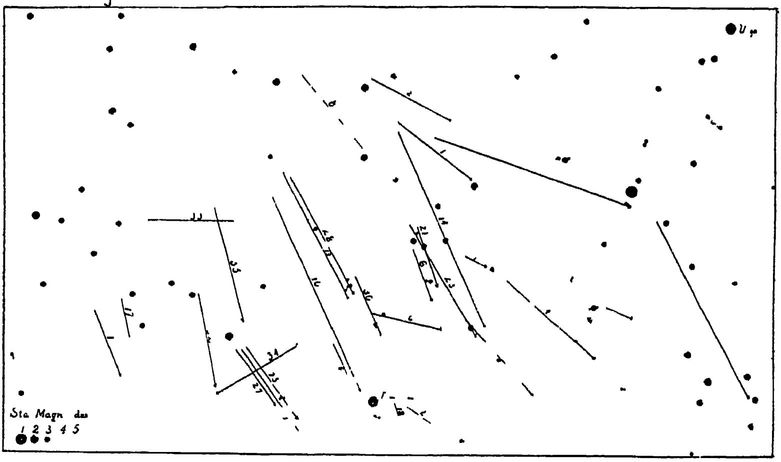
SIMULTANEOUS METEOR OBSERVATIONS

MADE AT MT HAMILTON AND MT DIABLO ON AUG 9 10, 1894

Derivation of the Formulæ for Determining Meteor Heights, and Application of the Same in the Reduction of the Meteor Observations of August 9 10, 1894

BY J M SCHAEBERLE

1894 Aug 9



1894 Aug 10

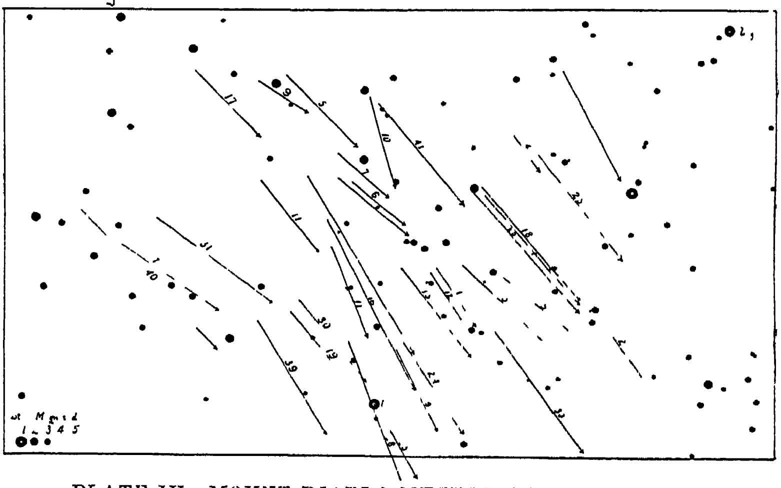


PLATE IV MOUNT DIABLO METEOR OBSERVATIONS OF AUGUST 9 AND 10, 1894

SIMULTANEOUS METEOR OBSERVATIONS,

MADE AT

MOUNT HAMILTON AND MOUNT DIABLO.

Derivation of the Formulæ for Determining Meteor Heights, and Application of the same in the Reduction of the Meteor Observations of August 9–10, 1894

By J M SCHAEBERLE

The observations discussed in the present paper were the first of the kind ever made at Mount Hamilton, and, indeed, the first that I, in common with the other observers, had ever made The results must, therefore, be considered in the light of preliminary work, which tends more to make plain the difficulties to be overcome in future observations than it does to increase our knowledge of the meteors

In our latitude the direction of the August meteors which can be conveniently observed, is such, that near the zenith the motion is always southwesterly, consequently the direction of a line joining the two observing stations should be northwesterly, if the most favorable conditions are desired To diminish the effects of personal errors of observations, the distance between the two stations should be of the same order of magnitude as the heights of the meteors Mount Diablo, a U S Coast Survey station, 40 miles from Mount Hamilton, and west of the north point, seemed to be the most suitable location for a second observer, it is 616 feet lower than Mount Hamilton, and is one of the most accurately determined stations in the United States

The observers at Mount Hamilton were Messrs COLTON and PERRINE, of the Lick Observatory Their methods of observation, etc , are fully described in their own words farther on.

Mount Diablo was occupied by myself, supplied with a time-

piece, and several tracings of a celestial chart, containing th easily visible naked-eye stars, on which the meteor paths wer inserted

The watch correction was determined daily by flash-ligh signals sent from the Lick Observatory

The method of meteor observation was as follows

The instant a meteor was seen, and its path with referenc to neighboring stars mentally noted, the observer commence counting (seconds) zero, one, two, etc , until the watch time o a particular count was obtained The correct time and meteo number were then recorded, and the meteor trail and numbe inserted on the map Miniature reproductions of the two map are given in Plate IV

I was alone on the mountain, and on both nights the obser vations were occasionally interrupted, in order to make prep arations for the greater comfort of both man and horse, the wind being unexpectedly strong and disagreeably cold Ther is absolutely nothing in the way of a building on the mountain top to afford shelter for man or beast During the day I was quartered at a small hotel, located about two miles from the summit

All my observations were confined to the south of the zenith and within thirty or forty degrees of the vertical plane passing through Mount Hamilton

In order to increase the chances of observing the brighter meteors the fainter ones were not recorded, as it was practically certain that the brighter ones at a given altitude would be the ones visible in the northern sky of Mount Hamilton, where they would probably also be of the same order of brightness The faintest ones seen at Mount Diablo were probably to the south of the Lick Observatory, and consequently, would not be observed there If, on the other hand, the faintness was due to causes not depending on the distance alone, the Mount Hamilton observers would be more likely to overlook the fainter ones, on account of the far greater number of meteors visible in the northern sky

In the reduction of these observations much time was wasted, owing to the fact that the published formulæ of KLINKERFUES were found to contain serious errors,* to which I have since called attention elsewhere

* See *Astronomical Journal* No. 25?

As there appears to be no easily accessible discussion of this particular branch of the meteor problem available in the English language, I have deemed it well to give, in a brief way, the successive steps leading up to the desired expressions

For determining whether the same meteor was observed at any two stations, the following two main conditions must be fulfilled

First—The times of observation must correspond to the same absolute instant

Second—The two points on the celestial sphere at which any particular point of the meteor's path—as, for instance, the beginning or end—are projected, must always lie in a plane which passes through both points of observation

The first condition is determined by simple inspection of the corrected times at the two stations

The meteor observations corresponding to the same absolute instants—allowing, of course, for the unavoidable errors of the observers in making their time estimates—are then to be examined to learn whether the requirements of the second condition are fulfilled

Let R_1 denote the distance from the earth's center to the first station,

Let φ'_1 denote the geocentric latitude of the first station,

Let θ_1 denote the local sidereal time of observation at the first station,

Let the corresponding quantities referred to the second station, be respectively R_2, φ'_2, and θ_2,

Let K denote the length of the straight line joining the two stations, and let A_2 and D_2 denote respectively the right ascension and declination of the point in which this straight line cuts the celestial sphere, as seen from the first station looking in the direction of the second station at the sidereal time θ_1

The rectangular coordinates of the two stations referred to the center of the earth and the celestial equator as the fundamental plane, with the + axis of X directed to the vernal equinox, the + axis of Y directed to a point in the equator whose right ascension is 90°, and the + axis of Z to the north pole, are then given by the expressions

$$X_1 = R_1 \cos \varphi'_1 \cos \theta_1 \quad (1)$$

$$Y_1 = R_1 \cos \varphi'_1 \sin \theta_1 \quad (2)$$

$$Z_1 = R_1 \sin \varphi'_1 \quad (3)$$

for the first station, and

$$X_2 = R_2 \cos \varphi'_2 \cos \theta_2 \tag{4}$$
$$Y_2 = R_2 \cos \varphi'_2 \sin \theta_2 \tag{5}$$
$$Z_2 = R_2 \sin \varphi'_2 \tag{6}$$

for the second station

If, now, we conceive the first station to be at the origin of a system of coordinates whose axes are parallel to those of the system above described, the corresponding coordinates of the second station referred to the first will evidently be the same as the difference between the geocentric coordinates of the two stations, so that we can write

$$K \cos D_2 \cos A_2 = X_2 - X_1 \tag{7}$$
$$K \cos D_2 \sin A_2 = Y_2 - Y_1 \tag{8}$$
$$K \sin D_2 = Z_2 - Z_1 \tag{9}$$

Substituting for the values of the terms in the second members the expressions given above, we have

$$R_2 \cos \varphi'_2 \cos \theta_2 - R_1 \cos \varphi'_1 \cos \theta_1 = K \cos D_2 \cos A_2 \tag{10}$$
$$R_2 \cos \varphi'_2 \sin \theta_2 - R_1 \cos \varphi'_1 \sin \theta_1 = K \cos D_2 \sin A_2 \tag{11}$$
$$R_2 \sin \varphi'_2 - R_1 \sin \varphi'_1 = K \sin D_2 \tag{12}$$

From which the distance K and the angles A_2 and D_2 can be readily found

As the value of A_2 increases uniformly with θ_1, the quantity $\theta_1 - A_2$ will be a constant for any two given stations, and corresponds to the hour-angle τ of the second station as seen from the first

If the coordinates of the second station are unknown, and it can be seen from the first station, the zenith-distance ζ and the azimuth ψ of the second station, as seen from the first, can be measured directly with a theodolite, and the distance, expressed in terms of any convenient unit, can be found by triangulation or from an official map The hour-angle τ $(= \theta_1 - A_2)$ and the declination D_2 can then be found by means of the expressions

$$\sin D_2 = \sin \varphi_1 \cos \zeta - \cos \varphi_1 \sin \zeta \cos \psi \tag{13}$$
$$\cos D_2 \cos \tau = \cos \varphi_1 \cos \zeta + \sin \varphi_1 \sin \zeta \cos \psi \tag{14}$$
$$\cos D_2 \sin \tau = \sin \zeta \sin \psi \tag{15}$$

In which φ_1 is the geographical latitude of the first station, which must then be reduced to geocentric latitude [for substitution in

equations (36), (37), and (38)] by the addition of the known quantity $\varphi'_1 - \varphi_1$ The distance between the two stations expressed in terms of any desired unit must be divided by the number of units in the earth's equatorial radius

Now, let α_1 and δ_1 denote respectively the right ascension and declination of a meteor as seen from the first station, and let α_2, δ_2 denote the place of the same meteor as seen from the second station, then the three points on the celestial sphere whose coordinates are A_2, D_2, α_1, δ_1 and α_2, δ_2 must all lie on the arc of the same great circle

Let I denote the inclination of this great circle to the celestial equator, and let ☊ denote the right ascension of one of the two points where the circle cuts the equator, then the following expressions must be satisfied within the limits of the errors of observation

$$\tan D_2 = \pm \sin (☊ - A_2) \tan I \tag{16}$$
$$\tan \delta_1 = \pm \sin (☊ - \alpha_1) \tan I \tag{17}$$
$$\tan \delta_2 = \pm \sin (☊ - \alpha_2) \tan I \tag{18}$$

If the upper sign + results from any one solution, the other two equations must also be satisfied with the plus sign, and *vice versa* Eliminating ☊ and I, we finally obtain the fundamental expression

$$\tan D_2 \sin (\alpha_2 - \alpha_1) - \tan \delta_1 \sin (\alpha_2 - A_2) + \tan \delta_2 \sin (\alpha_1 - A_2) = 0 \tag{19}$$

In actual practice, even when the same meteor is observed at both stations, equation (19) will not in general be exactly satisfied, owing to the unavoidable errors of observation Just how great an inequality of the two members of the equation may be allowed will depend largely upon the character of the observations and the relative positions of the three points The most expeditious procedure is to plot the three points* on a celestial globe, and see whether they lie on or near the arc of a great circle

If ρ_1 and ρ_2 denote respectively the distances of the meteor from the first and second stations, the meteor's rectangular equatorial coordinates referred to the first station as an origin, will be

*The point A_2D_2 is fixed relatively to the observer's horizon

$$x_1 = \rho_1 \cos \delta_1 \cos \alpha_1 \tag{20}$$
$$y_1 = \rho_1 \cos \delta_1 \sin \alpha_1 \tag{21}$$
$$z_1 = \rho_1 \sin \delta_1 \tag{22}$$

While the expressions for the meteor's coordinates referred to the second station as an origin, are

$$x_2 = \rho_2 \cos \delta_2 \cos \alpha_2 \tag{23}$$
$$y_2 = \rho_2 \cos \delta_2 \sin \alpha_2 \tag{24}$$
$$z_2 = \rho_2 \sin \delta_2 \tag{25}$$

Now, the difference between the two sets of coordinates for a given meteor must evidently always equal the difference between the coordinates of the two stations, so that we can at once write

$$\rho_1 \cos \delta_1 \cos \alpha_1 - \rho_2 \cos \delta_2 \cos \alpha_2 = K \cos D_2 \cos A_2 \tag{26}$$
$$\rho_1 \cos \delta_1 \sin \alpha_1 - \rho_2 \cos \delta_2 \sin \alpha_2 = K \cos D_2 \sin A_2 \tag{27}$$
$$\rho_1 \sin \delta_1 - \rho_2 \sin \delta_2 = K \sin D_2 \tag{28}$$

To obtain an expression for ρ_1 involving only known quantities, multiply equation (26) by $\sin \alpha_2$ and (27) by $\cos \alpha_2$, then subtracting one equation from the other, we readily obtain

$$\rho_1 = K \cos D_2 \frac{\sin (\alpha_2 - A_2)}{\cos \delta_1 \sin (\alpha_2 - \alpha_1)} \tag{29}$$

Similarly, by multiplying (26) by $\sin \alpha_1$ and (27) by $\cos \alpha_1$, and taking the difference, we have

$$\rho_2 = K \cos D_2 \frac{\sin (\alpha_1 - A\ )}{\cos \delta_2 \sin (\alpha_2 - \alpha_1)} \tag{30}$$

It will be noticed that when α_1 and α_2 are of nearly the same magnitude, or when they differ by nearly 180°, errors of observation will render the resulting values of ρ—found by means of equations (29) and (30)—extremely uncertain, so that these formulæ are not applicable when the parallactic displacement in right ascension is small

To obtain an expression for ρ for such cases, we proceed in the manner indicated by KLINKERFUES

Multiply equation (26) by $\sin \delta_2 \cos \alpha_2$, equation (27) by $-\sin \delta_2 \sin \alpha_2$, and (28) by $-\cos \delta_2 \cos 2\, \alpha_2$ Combining these equations so as to eliminate ρ_2, we obtain

$$\rho_1 = K \frac{\sin\delta_2 \cos D_2 \cos(\alpha_2 + A_2) - \cos\delta_2 \sin D_2 \cos 2\alpha_2}{\sin\delta \cos\delta \cos(\alpha_2 + \alpha_1) - \cos\delta_2 \sin\delta_1 \cos 2\alpha_2} \quad (31)$$

Similarly, if we multiply (26) by $\sin\delta_1 \cos\alpha_1$ and (27) by $-\sin\delta_1 \sin\alpha_1$ and (28) by $-\cos\delta_1 \cos 2\alpha_1$ and eliminate ρ_1, we get

$$\rho_2 = K \frac{\sin\delta_1 \cos D_2 \cos(\alpha_1 + A_2) - \cos\delta_1 \sin D_2 \cos 2\alpha_1}{-\sin\delta_1 \cos\delta_2 \cos(\alpha_2 + \alpha_1) + \cos\delta_1 \sin\delta_2 \cos 2\alpha_1} \quad (32)$$

In the expression for ρ_2, equation (32), the signs of the terms in the denominator are the opposite of those of the corresponding terms in (31), otherwise the two expressions are symmetrical

Let α, δ, and R denote respectively the geocentric right ascension, declination, and distance of the meteor The geocentric rectangular equatorial coordinates x, y, z, will then be given by

$$x = R \cos\delta \cos\alpha \quad (33)$$
$$y = R \cos\delta \sin\alpha \quad (34)$$
$$z = R \sin\delta \quad (35)$$

Now, each coordinate of the meteor referred to the center of the earth as an origin, is evidently equal to the corresponding geocentric coordinate of either station plus the coordinate of the meteor referred to the same station, so that we can at once write the equations

$$R \cos\delta \cos\alpha = R_1 \cos\varphi'_1 \cos\theta_1 + \rho_1 \cos\delta_1 \cos\alpha_1 = R_2 \cos\varphi'_2 \cos\theta_2 + \rho_2 \cos\delta_2 \cos\alpha_2 \quad (36)$$

$$R \cos\delta \sin\alpha = R_1 \cos\varphi'_1 \sin\theta_1 + \rho_1 \cos\delta_1 \sin\alpha_1 = R \cos\varphi'_2 \sin\theta_2 + \rho_2 \cos\delta_2 \sin\alpha_2 \quad (37)$$

$$R \sin\delta = R_1 \sin\varphi'_1 + \rho_1 \sin\delta_1 = R_2 \sin\varphi'_2 + \rho_2 \sin\delta_2 \quad (38)$$

Which serve to determine the values of α, δ, and R

The height h of the meteor above sea-level is then found from

$$h = (R - R') \cos(\varphi' - \varphi) \quad (39)$$

In which R′ is the radius-vector of our spheroid corresponding to the geocentric declination δ or the equivalent latitude φ', the

geographic latitude being φ But as $(\varphi' - \varphi)$ never exceeds 12′, equation (39) can be written without serious error

$$h = R - R' \tag{40}$$

Multiplying h by the length of the earth's equatorial radius, expressed in terms of any desired unit, the height of the meteor above sea-level will be given in terms of the same unit

To find the terrestrial west longitude λ corresponding to the right ascension α we have

$$\lambda = \lambda_1 + (\theta_1 - \alpha) = \lambda_2 + (\theta_2 - \alpha) \tag{41}$$

λ and δ $(= \varphi')$ being respectively the (west) longitude and latitude of that point on the earth's surface from which the meteor would be seen in the geocentric zenith

By plotting the values of λ and φ' for the beginning and end of the path, and having determined h for both ends, the azimuth of the vertical plane in which the meteor was moving, the inclination of its line of motion to the normal, and the resulting length of the visible path can be found graphically, and if the duration of visibility is given the velocity of the meteor also becomes known

At the close of this paper, in discussing the numerical results obtained from the simultaneous observations recorded farther on, I shall offer a few suggestions relating to methods of observation less liable to give erroneous results

In the following tables are recorded the number of the meteor, the Pacific standard time of observation, and remarks on the brightness, velocity, and angular length of the visible path

TABLE I

MOUNT DIABLO OBSERVATIONS OF THE AUGUST METEORS—*August 9, 1894*

No	Pacific Standard Time			Duration	Remarks
1	9^h	28^m	33^s	1^s	Very bright
2	9	45	16	¼	Very swift
3	10	10	46	¼	Short, bright
4	10	21	49	¾	Bright
5	10	40	36	1½	Long, bright
6	10	46	51	¼	Faint, swift
7	10	55	51	---	Not a Perseid Short and faint
8	10	58	59	1^s	Bright and long
9	11	9	36	----	Uncertain, seen by averted vision
10	11	28	53	1^s	Bright and long
11	11	55	59	¾	Bright Not very good
12	12	1	30	¼	Swift
13	12	7	31	¾	Long, bright, swift
14	12	11	31	---	Very bright
15	12	14	31±	¼	Very swift
16	12	23	31	---	Short, swift
17	12	(42)?	38	----	Minute may have been 43 Very short and very bright
18	13	4	31	---	Faint and swift
19	13	8	23	½	Bright and swift
20	13	9	16	----	Bright and swift
21	(13	13	11)	---	Swift Not very good
22	13	14	43	---	Faint and swift
23	13	30	41	---	Bright
25	13	37	31±	---	Swift
28	14	3	11	---	Swift
30	15	19	11	----	Swift
31	15	24	46	----	Swift
32	15	29	13	----	Swift
33	15	37	41	---	Swift and bright
34	15	41	7	2^s	Slow and bright
35	15	49	21	---	Bright
36	16	11	1	----	A very bright meteor from Cassiopeia to Job's Coffin In bursting it illuminated surrounding country, although the morning twilight was already very strong

TABLE II

MOUNT DIABLO OBSERVATIONS OF THE AUGUST METEORS—*August 10, 1894*

No	Pacific Standard Time			Duration.	Remarks
1	9^h	10^m	45^s	1^s	Long, bright, swift
2	10	43	27	- -	Swift
3	10	46	47	----	Swift Not bright
4	{10	49	32	---	Faint
	{10	51	17	---	Faint, swift
5	10	55	2	-- -	Swift
6	11	7	35	---	Faint
7	11	9	44	----	
8	11	9	58	--	Long, bright
9	11	21	34	----	Swift
10	11	22	42	---	Swift, bright
11	11	29	2	---	
12	{11	30	32	---	
	{11	34	02	- -	Long, bright
13	[11	14	44]	--	Bright, swift, and long
15	11	45	42	----	
16	12	0	±	---	Very long, very bright
17	12	5	57	---	
18½	12	13	2	--	Bright
19	12	13	22	---	Very bright
20	12	38	32	--	Long and very bright
21	12	40	2	--	
22	12	42	32	---	Long and very bright
24	12	59	51	- -	Bright Several meteors lost before this one
25	13	6	32	---	Bright Lost one after this near Fomalhaut
27	13	11	42	--	Swift
28	13	20	22	---	Bright
29	13	20	27	---	Bright Follow each other quickly A third one in same neighborhood not mapped
30	13	22	47	--	Very bright
31	13	32	32	----	Very bright
35	13	46	54	--	Short, quick
36	14	17	32	---	Swift
38	14	22	2	----	Very bright Exactly through Fomalhaut
39	14	25	57	----	Bright
40	15	6	32	----	Swift, bright
					At about 10^h $22^m \pm 3^m$ a very bright meteor in Scorpio left a train visible for 10^s

The corrected time corresponding to each meteor path observed at Mount Diablo was first compared with the times recorded at Mount Hamilton, and wherever as a rule the two times differed by less than 10^s, both meteor paths—as seen from the two stations—were plotted on a star map and the coordinates, right ascension and declination, of both ends of the path read off and recorded for each station

These coordinates were then transferred to a celestial globe, together with the point in declination D_2, having the right ascension A_2 at the sidereal time of observation θ_I If the same meteor was observed at both stations, then of the two great circles passing through the point A D_2, one must pass through the two projections of the beginning of the path, and the other great circle must pass through both ends (in projection) of the same path, allowing for possible deviations due to personal and other errors of observation

Whenever these conditions were not fulfilled, no further attention was paid to that particular set of observations

The pairs of observations, which *a priori* seem to belong to the same meteor, are given in the two following tables, together with the coordinates of the beginning and end of each observed path

TABLE III

MOUNT DIABLO OBSERVATIONS

Date	Meteor No	Pacific Standard Time	Beginning		End	
			α_2	δ_2	α_2	δ_2
Aug 9	8	10^h 58^m 59^s	358° 5	+31° 5	344° 5	+16° 0
9	20	13 9 16	343 0	−14 7	330 0	−17 0
9	28	14 3 11	359 0	+13 0	346 0	− 8 5
9	31	15 24 46	33 0	−14 0	28 0	−26 0
9	33	15 37 41	34 0	+ 3 0	8 0	+ 2 5
9	35	15 49 21	12 0	+ 5 5	7 0	−17 0
10	4	10 51 17	318 5	+20 5	312 0	+12 5
10	7	11 9 44	350 0	+16 0	342 0	+ 7 0
10	9	11 21 34	4 5	+28 5	355 5	+23 0
10	18½	12 13 2	323 5	+ 9 5	306 0	−12 0
10	39	14 . 25 57	4 0	−15 5	351 5	−37 0
10	40	15 6 32	40 0	+ 9 0	12 0	−21 0

TABLE IV

MOUNT HAMILTON OBSERVATIONS

Date, 1894	Meteor No	Pacific Standard Time	Beginning		End	
			α_1	δ_1	α_1	δ_1
Aug 9	38	10h 59m —s	18° 5	+55° 5	353° 5	+50° 5
9	120	13 9 10	311 0	+45 0	305 0	+36 0
9	166	14 3 12	347 0	+31 0	336 0	+20 0
9	220	15 24 54	350 0	+82 0	126 0	+85 0
9	227	15 37 32	28 0	+63 5	323 0	+63 5
9	232	15 49 18	348 5	+28 0	336 5	+16 0
10	33	10 51 7	268 0	+78 5	261 0	+85 0
10	43	11 9 43	165 0	+70 5	167 5	+64 5
10	53	11 21 29	17 5	+57 5	8 0	+54 0
10	94	12 12 57	277 5	+62 5	265 ±	30 ±
10	276	14 26 9	292 5	70 0	272 0	61 0
			287 0	66 5	278 5	59 5
10	333	15 6 40	260 0	73 5	244 0	65 0
			260 0	76 0	249 5	65 0

Of the two sets of coordinates given for Nos 276 and 333, the upper figures refer to Mr COLTON's observations, the lower ones to those of Mr PERRINE, both observers having in these two cases recorded the same meteors In the reductions the mean values were used

The numbers corresponding to observations of presumably the same meteor are, therefore 8–38, 20–120, 28–166, 31–220, 33–227, 35–232, 4–33, 7–43, 9–53, 18½–94, 39–276, and 40–333 This notation will be used to designate any particular meteor under discussion

REDUCTION OF THE OBSERVATIONS

As I have taken Mount Hamilton as the first station, all the symbols having the subscript 2 will, therefore, refer to the Mount Diablo end of the base line

The following quantities are deduced from data given by the U S Coast and Geodetic Survey (see *Publications of the Lick Observatory*, Vol I, page 175)

Geographic:
- Longitude of Mt Hamilton $= \lambda_1 = 121° \; 38' \; 35'' \; 8$
- Latitude of Mt Hamilton $= \varphi_1 = +37 \; 20 \; 24 \; 8$
- Latitude of Mt Diablo $= \varphi_2 = +37 \; 52 \; 48 \; 7$

Distance of Mount Diablo from Mount Hamilton = 40 095 geographical miles

Azimuth of Mount Diablo from Mount Hamilton $= \psi = 158°$ $17' 45''$, measured from the south point towards the west

I found that the logarithm of the terrestrial radius-vector R_1 for the Lick Observatory, as published in the various Nautical Almanacs, refers to sea-level for both the BESSEL and CLARKE spheroids, it is therefore in error by about eight-tenths of a mile, or 874 units of the seventh decimal place of $\log R_1$ The correct value of $\log R_1$ I find to be

$$\log R_1 = 9\ 99956$$

And for Mount Diablo I find the value

$$\log R_2 = 9\ 99954$$

To find K we divide 40 095 by the number of miles in the earth's equatorial radius, and obtain

$$\log K = 8\ 00509$$

Next, to find the true zenith-distance ζ of Mount Diablo as seen from Mount Hamilton it is required to find the angle $(180° - \zeta)$ opposite the side R_2 in the plane triangle whose sides are R_1, R_2, and K This will be given by the expression

$$\sin \tfrac{1}{2} (180° - \zeta) = \sqrt{\frac{\frac{1}{2}(R_2 + R_1 - K)\ \frac{1}{2}(R_2 - R_1 + K)}{2\ R_1\ K}} \quad (42)$$

From which we obtain

$$\zeta = 90°\ 23'\ 40''$$

Substituting the above values of φ_1, ψ, and ζ in equations (13), (14), and (15), we obtain

$$D_2 = 47°\ 15'\ 9$$
$$\tau = \theta_1 - A_2 = 146°\ 58'\ 6$$

Consequently for any given observation at the sideral time θ_1 we have

$$A_2 = \theta_1 - 146°\ 58'\ 6$$

Had all the coordinates of Mount Diablo been given, equations (10), (11), and (12) would have been used to find K, D , and A The resulting value of A_2 would then correspond to the assumed sidereal time θ_1 at Mount Hamilton, or $\theta_2 = \theta_1 - (\lambda - \lambda_1)$ at Mount Diablo

The above computed values of τ and D_2 were the ones used in the preliminary tests for determining whether the same meteor was observed at both stations, and by means of which those observations given in Tables I and II were selected as fulfilling the two main conditions

The values of ρ_1 and ρ_2 can now be found by means of equations (31) and (32), in preference to those of (29) and (30), as the parallactic displacements are greater in declination than they are in right ascension If the resulting values of ρ_1 and ρ_2 were exact—that is, if there were no errors of observation—the substitution of either ρ_1 or ρ_2 in equations (36), (37), and (38) would result in the same values of R, α, and δ

Owing to the errors of observation, however, more accurate results will be obtained by using the values of ρ_2 in the present case, as the Mount Diablo observer's line of vision was more nearly at right angles to the meteor paths than was the case for the observers at Mount Hamilton As the direction of vision at the latter place was less inclined to the meteor paths, a given error of observation will cause a greater error in the final result [found by means of equations (36), (37), and (38)] if we use the observed values α_1, δ_1, than it will if the quantities α_2, δ_2 are substituted

I have consequently taken as the adopted values of h, α, and δ those which result from the substitution of ρ_2 in equations (36), (37), and (38) In order, however, to illustrate how much the errors of observation change the character of the computed results, the abnormal cases have been re-computed, using the value of ρ , instead of ρ_2

In each case I have added the data —azimuth, —inclination to the normal and actual length of visible path, thus giving the complete determination of the meteor's motion relatively to the earth's surface The coordinates, latitude (φ) and longitude (λ), are geographical, the angle φ being found from

$$\varphi = \varphi' + 0^\circ\ 11'\ 3$$

φ' being the same as the geocentric declination δ given by equations (36), (37), and (38) λ is the longitude west from Greenwich h is the height in miles ψ and ι are, respectively, the azimuth and zenith-distance of the point towards which the meteor is moving L is the actual length of the meteor's visible path expressed in miles

TABLE V

ELEMENTS OF METEOR PATHS

No of Meteor	Beginning: Latitude φ		Beginning: Longitude λ		Beginning: Height h	End: Latitude φ		End: Longitude λ		End: Height h	Azimuth of Plane of Motion ψ	Inclination to Normal i	Actual Length of Visible Path L
					Miles					Miles			Miles
8–38	38°	1′ 7	120°	35′ 6	56 64	37°	40′ 1	120°	49′ 4	51 01	27°	101°	29
[20–120]	37	22 1	121	30 8	[27 44]	37	12 5	121	42 2	[38 75]	[46]	[51]	[20]
28–166	37	13 1	121	15 2	104 82	37	5 3	121	41 0	53 87	70	154	59
31–220	37	44 3	121	26 0	24 87	37	46 7	121	41 0	3 65	101	148	26
33–227	37	36 5	121	23 6	27 62	37	34 7	121	40 4	29 09	81	85	16
35–232	37	13 1	121	42 2	74 62	37	40 7	121	43 4	27 73	176	141	48
4–33	37	44 9	121	27 8	31 85	37	43 7	121	32 0	22 21	72	150	11
[7–43]	37	50 3	121	37 4	[11 69]	37	49 1	121	30 8	[8 49]	[287]	[121]	[7]
9–53	37	55 7	120	56 6	35 71	37	51 5	121	21 8	16 53	80	130	30
18½–94	37	38 9	121	36 8	27 10	37	23 3	121	51 8	29 28	38	85	22
[39–276]	37	30 5	121	32 6	[19 83]	37	49 1	121	38 6	[1 37]	[165]	[131]	[29]
40–333	37	49 1	121	30 8	9 23	37	46 7	121	37 4	4 56	67	121	9

To assist in deciding whether the especially abnormal results (cited below), for some of the cases of the above table, are simply caused by errors of observation, or whether they are due to the fact that the same meteor was not observed at both stations, new heights were computed, using data referred to the Mount Hamilton end of the line K That is, in equations (36), (37), and (38) the expressions containing the subscript 1 were used, instead of those having the subscript 2, the latter were employed in obtaining the results given in Table III

Nos (20–120) These observations possibly refer to two different meteors The new heights also make the end of the path higher than the beginning

Nos (28–166) This can hardly be called an abnormal case, but as the height at beginning is considerably greater than the average of the others, I computed the new values and obtained 68 30 and 50 63 miles for the beginning and end, respectively, so that it is practically certain that both observations refer to the same meteor, the discordance between the first and the new values of the height at the beginning being due to errors of observation

Nos (33–227) Doubtless refer to the same meteor, for the new heights make the meteor approaching, we find for the beginning $h = 29^{m}\,36$, and at the end $h = 27^{m}\,25$

Nos (35–232) The azimuth is discordant, but probably due to errors of observation, as the new azimuth is still more discordant, while the new heights agree fairly well with those given above, being for the beginning $78^{m}\,41$, and for the end $34^{m}\,14$

Nos (7–43) Probably refer to two different meteors, the tabulated azimuth is very discordant

Nos (18½–94) Same meteor, same remarks as for (33–227), the new heights are $32^{m}\,95$ and $27^{m}\,25$ for beginning and end, respectively

Nos (39–276) Probably refer to two different meteors, as the azimuth is discordant, and one of the heights is improbable, the new heights are $16^{m}\,80$ and $0^{m}\,72$—also an improbable result The difference between the times of observation, 12^{s}, is also suspiciously large

Nos (40–333) Probably same meteor The new values are at beginning, $h = 25^{m}\,86$, at end, $h = 10^{m}\,59$ That this large

deviation from the tabular values can be accounted for by the errors of observation, will be apparent from an inspection of the data given in Table IV, from which some idea can be gained as to the magnitude of these errors

For both No 276 and No 333 two different observers recorded the positions of the same meteors From these figures we learn that an actual error of 2° of a great circle is by no means improbable

For critical positions an error of this magnitude may evidently cause the formulæ to give absurd or impossible results for the height of a meteor actually observed at both stations, without even taking into account certain other errors due to physical causes wholly independent of the observer's estimates

A consideration of the apparent diurnal motion of the August meteor radiant, with reference to a point in the latitude of the Lick Observatory, will make it plain that all the true azimuths, while the sun is below the horizon, must lie in the first quadrant The actual angle is, of course, variable, it reaches its maximum value, 46°, at about two hours after midnight The inclination to the normal (zenith-distance) continually increases with the possible time of observation, the maximum value, 162°, being attained about sunrise

The differences between the observed results and those which would be obtained on the hypothesis that all the meteors enter our atmosphere along lines which were originally parallel, are mostly due to errors of observation It is evident, however, that if the meteors are not spherical in shape, or if the spherical ones are revolving very rapidly, they will be more or less deflected, on entering our atmosphere, from the path they would take if no atmosphere were present.

By taking the mean of the several unbracketed elements, height and length of path, given in Table V, a general idea of the mean position and motion in our atmosphere can be obtained We thus find for the apparent motion of an August meteor the approximate quantities

Mean height of a meteor when first seen	= 43 6 miles
Mean height of a meteor when last seen	= 26 4 miles
Mean length of the visible path	= 27 8 miles
Mean duration	= 0^s 77

The last quantity being the mean of the fifteen estimates of the time required for the meteor to describe its visible path, according to the observations of the Mount Diablo observer

Assuming the above value, 27 8 miles, for the mean length of the visible path, there results—

Mean velocity of the August meteors = 36 miles per second

Of the meteors given in Table V only the duration of (8–38) happens to have been recorded by the Mount Diablo observer, the time is 1^s, and the computed length of the path 29 miles

These observations were made more for the purpose of determining the heights of the meteors than for any other element, this accounts for the fact that so few estimates of the duration times were made For computing the orbit of a meteor the velocity must be accurately known, if reliable elements are wanted

To obtain the true direction and velocity of motion of a meteor in its own orbit, while in our atmosphere, we must eliminate the aberrational effects due to the orbital motion of the earth Having once found the meteor's orbital velocity, all the elements of the orbit can at once be computed

The uncertainty in the velocity of the August meteors is so great—even for the best results that have been secured—that only a most rude approximation to the true elements need be expected

As the velocity (36 miles), adopted as the motion in our atmosphere in one second of time, is derived from a mean of all the results of the 1894 observations, I shall assume a mean value of all the other data necessary for the computation of the orbit

For determining the coordinates of the point from which the meteors appear to be coming, it will evidently be best to use all the observations made in the northern sky of Mount Hamilton

According to the observations of Messrs COLTON and PERRINE, the apparent radiant of the August, 1894, meteors had the coordinates

$$\text{Right Ascension} = 46^\circ$$
$$\text{Declination} = +55^\circ$$

As the elements will be referred to the plane of the ecliptic these coordinates are to be converted into latitude and longitude

by means of the usual formulæ So that as seen from the earth the meteors apparently radiate from a point in

Longitude 60° 5
Latitude + 36° 0

From the Nautical Almanac we find that the earth, as seen from the sun at about the mean of the times of observation, was in longitude 317° 5, the latitude being practically zero It was, therefore, moving towards a point in

Longitude 48° 0
Latitude 0° 0

to the nearest half degree, allowing for the inclination of the earth's direction of motion to its radius-vector

From the above positions we find that the angular distance between the point towards which the earth is actually moving and that from which the meteors *appear* to be coming is

37° 82

and the inclination of the great circle (joining the two points) to the ecliptic, 73° 42 *

Now (applying the principle of the parallelogram of velocities) in the plane triangle whose sides are 18 (the velocity of the earth in its orbit) and 36 (the velocity of the meteor in our atmosphere), with the included angle 37° 82, it is required to find the side V opposite the known angle, and the inclination *s* of this side to the side 18 Hence

$$V = 24\ 5$$
$$s = 64°\ 60$$

V corresponds to the lesser of the two diagonals of a parallelogram whose sides are 18 and 36, the actual angle between the sides being 180°+37° 82, as the meteor radiant is 180° from the point towards which the meteors would appear to converge if the apparent paths were continued indefinitely

For the given motion in our atmosphere the actual velocity

*Found by solving a right angle spherical triangle, the sides about the right angle being 12° 5 (= 60° 5 — 48° 0) and 36° 0 The required quantities are, the hypothenuse and the angle opposite the side 36° 0, or, 37° 82 and 73° 42 respectively

of an August meteor in its own orbit is, therefore, 24 5 miles per second, and the true angle between the line of the earth's motion and that along which a meteor is moving is

$$64° 60 + 180° = 244° 60$$

Lastly, to completely determine the direction of the line along which the meteors are moving it is necessary to find the angle which this line makes with a line drawn to the sun In the spherical triangle formed by joining the three points on the celestial sphere—one being in the direction of the sun, the second, that towards which the earth is moving, and the third, that towards which the meteors are moving—we have given the two sides 48° — 137° 5 = 270° 5 and 64° 60, and the angle 73° 42 opposite the side 64° 60, to find the third side, which is the measure of the required inclination The solution gives 254° 84 as the required angle

We thus have given the orbital velocity of a body at the earth's distance from the sun, and the true direction of motion, from these three constants we can now compute all the elements of the orbit (which would subsequently be described by this body if left undisturbed by the earth) by the usual methods

From these given data, depending upon the Mount Hamilton and Mount Diablo observations, I have computed the following

ELEMENTS OF THE AUGUST METEORS

Longitude of the Perihelion	= 349° 8
Longitude of the Ascending Node	= 137° 5
Inclination of the Plane of the Orbit	= 116° 2
Eccentricity	= 59° 2
Semi-Major Axis	= 6 58
Perihelion Distance	= 0 92
Periodic Time	= 17 0 years

The semi-major axis and the perihelion distance are expressed in terms of the earth's mean distance from the sun as a unit

To give a forcible idea of the degree of uncertainty of the interrelated elements—eccentricity, semi-major axis, and periodic time—it is only necessary to state that if an orbital velocity one mile greater than that used is assumed, the path

becomes parabolic The probable error of even the best determined velocity of a periodic meteor is much greater than one mile A computer who gives the periodic time in the neighborhood of one hundred years, therefore, assumes that the observed velocity is known to within a small fractional part of a mile

The agreement between the periodic times of computed meteor orbits and certain known comet orbits, on which some of our text-books lay great stress, is apt to be very misleading The longitude of the Node is, of course, well determined, the only other element which can be said to be even approximately known, is the inclination of the orbit

CONCLUDING REMARKS

To obtain reliable data for finding the actual orbits of the meteors, much more refined methods of observation must be devised than any that have been used up to the present time All results depending on naked-eye estimates can only be regarded as the rudest approximations

When, as in the case of the series discussed in the present paper, the distance between the two stations is large, a given meteor may and doubtless does become visible to one observer before the other can possibly see it The error (which is not a personal one) introduced in the reduction of such observations results from the fact that points of beginning (or ending) as seen from the two stations do not correspond to the same actual position of the meteor, the error may at times easily amount to several degrees of arc

The only satisfactory remedy seems to be that the distance between the two observers must be relatively small, and all the observations confined to meteors which pass within a few degrees of the zenith

While it is manifestly certain that all known naked-eye methods for determining the heights would be of but little value in cases where the distance between the stations is only a mile or two, it would seem that great accuracy in the position of a meteor could be obtained if two equatorially mounted photographic telescopes of exactly the same size could be used simultaneously, one being at each end of a short, but accurately determined base line The only difficulty in the way of

such a plan at the present time is the lack of the required degree of sensitiveness of the photographic plate The extremely short duration of the meteor's light at any given point of its path has thus far made it impossible to secure reliable photographic trails of the fainter meteors, and the chance of getting a very bright meteor in a given region of the sky is quite small *

As the makers of dry plates are, however, continually increasing the degree of sensitiveness of their emulsions, we may soon be able to obtain satisfactory data from a photographic study of the meteors Having, in some such way, secured accurate data for finding the heights, direction, and length of the visible path, it is just as necessary to employ some extremely accurate method for determining the interval of time required for the meteor to traverse its visible path, if a reliable orbit is desired When these improvements have been perfected, certain other quantities depending upon the earth's attraction, the diurnal velocity of the observer, the resistance of our atmosphere, etc, must be allowed for

J M SCHAEBERLE

Lick Observatory, October, 1895

* While on Mount Diablo I exposed a number of plates, in a stationary landscape camera, directed towards Mount Hamilton, and elevated 40° Each plate was exposed about 2^h, the stars being allowed to trail across the plate during the whole time, but on the plates developed no meteor trails were found During the same nights Messrs COLTON and PERRINE also exposed plates in a similar camera directed towards Mount Diablo, and also elevated about 40°, with the same negative result The field of view was about 40°, the diameter of the objectives, 1⅝ inches, and the focal lengths 11 inches

OBSERVATIONS OF THE AUGUST METEORS

AT THE LICK OBSERVATORY

By A L COLTON

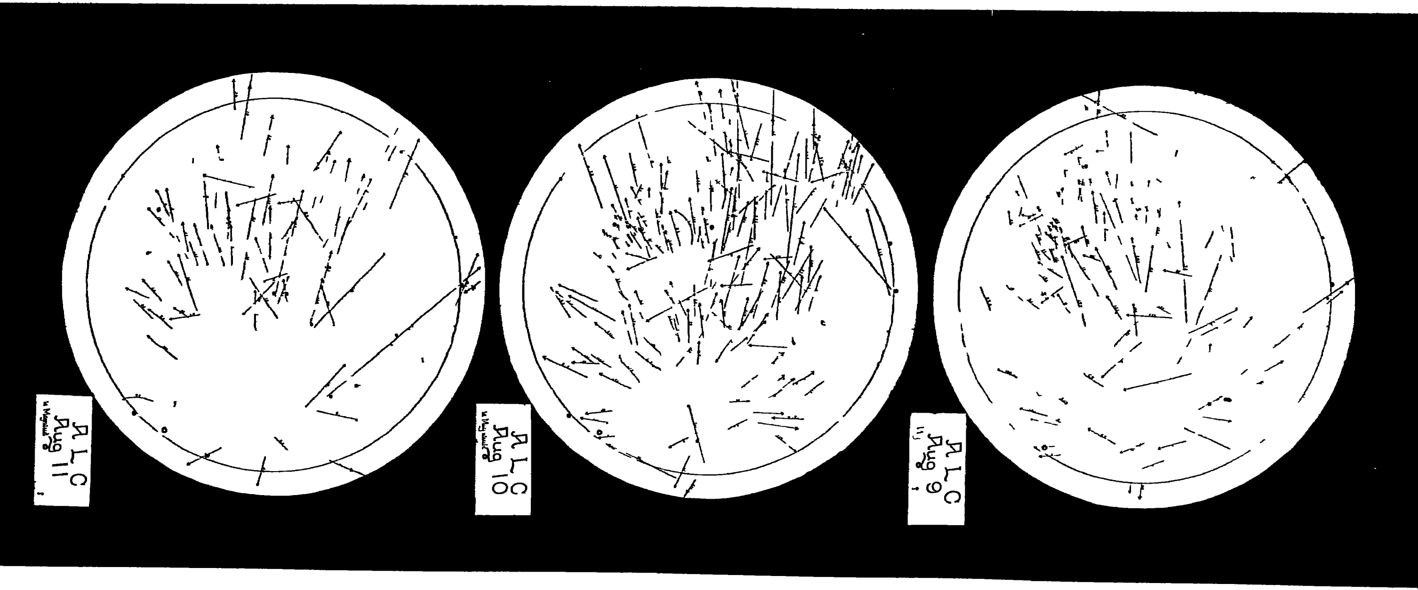


PLATE V METEOR PATHS OBSERVED AT THE LICK OBSERVATORY
By A L Colton 1894, August 9, 10, 11

OBSERVATIONS OF THE AUGUST, 1894, METEORS AT THE LICK OBSERVATORY.

By A L Colton

The observations of meteors in the northern sky made by me on the nights of August 9, 10, and 11, 1894, with Mr C D Perrine, were undertaken at the suggestion of Professor Schaeberle, who proposed to observe from the summit of Mount Diablo at the same time Mount Diablo is about 41 miles from Mount Hamilton, in a direction 23° west of north, height 3,800 feet, and simultaneous observations of the Perseid meteors were made with a view to determining the heights of any seen in the region of sky between the two stations

For recording the paths of the meteors observed, I constructed a circumpolar chart on a scale one half greater than that in Proctor's larger star atlas, locating the positions of stars of the fourth magnitude and brighter, and a few of the fifth More stars on the chart, say all of the fifth magnitude, could have been used to good advantage From this chart others were made, the star-dots being located by needle-perforations For each night's use a chart was so mounted on an easel that it could be rotated to correspond to the positions of the stars represented

My charts included the sky to 45° polar distance, while those made and used by Mr Perrine were on a smaller scale, but extended to 60° polar distance Their greater extent proved very useful, as more meteors could be recorded, especially near the zenith, where they were of most importance for the original purpose of the observations

Our work on the nights named was shared by Mr W F Poole, who acted as recorder, noting the time by a chronometer, and calling back to us the serial number of the meteor observed This number was appended to the arrow drawn on the chart to indicate the meteor's path As it was necessary to announce very promptly the meteors seen, and some of them were beyond the range of our charts, or so poorly observed as not to be worth

recording, the charts do not represent all the meteors noted The same record answered for both observers, and naturally enough it often happened that not the same meteor was seen by both Sometimes we noted different meteors at the same instant I observed a few beyond the range of my chart, but recorded them upon Mr PERRINE'S

I endeavored to record as accurately as possible the length of each path, noting the points of beginning and ending by their proportional distances between the surrounding stars The length of path seemed to me important, in view of the effort to locate relatively to the earth's surface the position of the meteors Had the position of the radiant been the only object sought, the length of path would have been less important, and perhaps the direction could have been more accurately recorded A few paths especially well observed are denoted by a + sign, and a few somewhat in doubt, by an interrogation point

About one fifth of the whole number recorded by me came from other regions than *Perseus*, and are distributed quite evenly through the series of observations They seem to offer no opportunity for the location of radiant points

By means of pencil lines on the charts the arrows radiating from *Perseus* were produced backward to that constellation At first glance it seems impracticable to locate a well-defined radiant among them, but a closer inspection shows points where the lines intersect much more frequently than elsewhere Some of these intersections may readily be disposed of as accidental The following table gives the location of the more conspicuous

August 9			August 10			August 11		
No	R A	Dec	No	R A	Dec	No	R A	Dec
1	21°	51°	7	17°	61°	17	38°	53°
2	25	50	8	24	59	18	44	56
3	40	62	9	26	55	19	50	58
4	46	55	10	31	67	20	51	63
5	48	52	11	34	53	21	52	52
6	53	64	12	37	57			
			13	45	57			
			14	47	61			
			15	48	53			
			16	56	71			

The existence of such centers might be accounted for, as Mr DENNING says (*Popular Astronomy*, 1 270), "There are certainly more than one hundred distinct meteor streams in

active play on about August 10 (say between August 5 and 15), and the radiant positions of many of the more prominent of these have been ascertained in a satisfactory manner" Then follows a table of positions of seventy-two of these radiants, and a diagram showing the location of thirty-four of them Unfortunately, if corroboration be sought from Mr DENNING's table, the positions agree, even approximately, only in the case of the Perseid radiant proper

The most prominent intersections on my charts for the three nights respectively, as recorded above, are Nos 4, 13, and 20 Nos 4, 13, and 18 agree quite closely with each other, and with the most conspicuous radiant point located by Mr PERRINE on his chart of August 10 Thus, from independent records, made by somewhat different methods, we have reached practically the same result

My charts afford no support to the theory of the progressive shifting of the radiant from day to day The case might have been otherwise, perhaps, if a greater number of meteors had been recorded on the nights of the 9th and 11th, or if several more nights had been included in the series of observations

During these observations I exposed a series of plates in an ordinary camera, in view of the possibility of obtaining photographic records of the brightest meteors, but without success On the night of August 2, about a week before these observations, I exposed two plates in the same camera, directed vertically upward, for about two hours each, to test the capacity of the lens for recording star-trails A much brighter meteor than any seen during these observations crossed the field of the lens, but left no trace upon the sensitive plate I was, therefore, not disappointed at not obtaining a photographic record of any of the Perseid meteors Five meteor-trails, nearly all faint, were obtained during this shower by Professor BARNARD, using the 6-inch Willard lens—an instrument of immense light-gathering power, as compared with the small objective used by myself Three of these, one of them being of a "stationary" meteor, were found on a plate exposed August 9, with the lens directed to the radiant, and one trail was obtained on each of the two following nights, with the lens directed to *Sagitta* and *Lyra*, respectively

I used a Beck lens of about 11 inches focus, with the full

aperture of about $1\frac{5}{8}$ inches and $6\frac{1}{2} \times 8\frac{1}{2}$ plates On August 7 some plates were exposed with the lens pointed vertically, and on the four following nights with the lens at an angle of 45° to the horizon, and in the general direction of Mount Diablo In this direction the average angular velocity of the meteors is presumably greater, and the duration less, than at the radiant, much farther east The pole-star was just within the eastern limit of the field of my lens The plates used were Seed 26 and Cramer "Crown," and each was exposed two or three hours Neither Professor SCHAEBERLE nor Mr PERRINE, both of whom used view-lenses in a similar manner, secured any meteor-photographs

It is evident that ordinary view-lenses are useless for the study of meteor-swarms, such as the Perseids The meteors are faint—evidently such small particles as might be expected in the debris of comets—while the exceptionally brilliant meteors occur singly, and presumably consist of large masses As matters stand, we have not yet reached the time anticipated in a rather skeptical paragraph by Prof H M PAUL (*Science*, 8 132), in which he says "With to-day's doubtful methods of mapping the tracks of meteors, our opinion is that we must wait till some Argus-eyed camera * * * shall decide by the doctrine of probabilities as to the real existence of nine tenths of the so-called 'radiants' of to-day "

I exposed thirteen plates, including those of August 2 The exact details of exposure are unnecessary, but some of the results may be of interest, as bearing on the capacity of ordinary view-lenses for recording star-trails With lens and plate of the dimensions previously stated, using the full aperture, it is readily understood that a star trailing across the plate could not long remain accurately in focus The trails were quite sharp at the center of the plate, but with increasing distance from the center they broadened and became correspondingly fainter The available area varied with different plates, but at least an inch or two of margin should in every case be omitted as worthless For examination two plates were selected, one exposed to the zenith, the other to the polar region Owing to the slower motion of the star images, the trails upon the latter were much the stronger Those crossing the center of this plate were made by stars having a declination of about 70° In

this region a star of the third magnitude (D M 65° 1170) left a trail 0^{mm} 154 in width as measured under the microscope, while a sixth magnitude star (D M 72° 818) gave a trail 0^{mm} 080 wide On this plate 110 trails are identified, 29 being of fainter magnitudes than the sixth, and one of the ninth (D M 70° 976) Still fainter trails are visible, but cannot be identified, they probably belong to stars of the tenth magnitude Between the center of the plate and the polar region at the end there is apparently little difference in the faintest magnitudes recognized, the decrease of illumination caused by the broadening of the trails seems to be compensated by the longer exposure The trail of an eighth magnitude star (D M 88° 104) was identified within an inch of the end of the plate

On the plate exposed to the zenith 53 trails are identified, made by stars in the constellations *Lyra* and *Cygnus*, the faintest being of the seventh magnitude Near the middle of the plate the multiple star ε *Lyræ* gives a very pretty pair of trails 0^{mm} 28 from center to center

On the night of August 7 Professor SCHAEBERLE exposed a 6½ x 8½ Seed 26 plate to the polar region, using a Beck lens similar to my own, and has placed it in my hands for examination in this connection It affords a better opportunity for examining polar trails, as the pole is but little more than an inch and a half from the center of the plate The trails are numerous and well defined In the central portion of the plate, occupying perhaps a third of the area, 144 trails were identified, of which 121 were made by stars of fainter magnitudes than the sixth Four of these trails were made by two stars each, and one by three stars, the stars being in these cases so close together that their trails were not separable Including one of the double trails, 82 were within 5° of the pole, as given in the Durchmusterung The D M positions are given for the epoch 1855 0, and the pole is now about 13′ distant from its position at that time This change does not interfere with the general purpose of the discussion, it did, however, make still more difficult the tedious process of identifying faint trails near the pole

All the stars located by means of their trails were identified in the D M catalogue and charts, with a single exception—a star of about the tenth magnitude, which Professor TUCKER has

kindly observed for me with the meridian circle. He finds its position for 1895.0 to be R. A. = $7^h\,17^m\,55^s$, Dec. = 89° 45′ 56″. I have computed the precession since 1855.0, and find its position for that date to be R. A. = $3^h\,45^m\,37^s$, Dec. = 89° 44′ 6″. It is not included in the Durchmusterung, nor in CARRINGTON's catalogue of circumpolar stars.

The magnitude of the faintest stars identified is 9.5, of which there are two, both within a degree of the pole. There are about twenty others of the ninth magnitude and fainter, all within 7° of the pole.

Reference has been made to the broadening of the trails with increasing distance from the center of the plate. A conspicuous illustration of this is afforded by the trail of *α Lyræ*, on the plate exposed to the zenith. The trail of this star, commencing at a little more than an inch from the center of the plate, with a width of $0^{mm}.156$, increased to $0^{mm}.656$ in a distance of less than 2½ inches (about 12°). The narrow end of the trail was attended by a darkish border, evidently caused by irradiation, which nearly or quite disappeared before reaching the broad end, thus showing the greater brilliancy of the image where best in focus.

In the central region of this plate four trails were selected for measurement, and gave the following results:

	Mag.	Width of Trail	
D. M. 32° 3286	3.2	$0^{mm}.056$	(λ Lyræ)
D. M. 34 3590	4.6	0 .052	(8 Cygni)
D. M. 34 3798	4.2	0 .056	(η Cygni)
D. M. 36 3557	5.0	0 .052	(4 Cygni)

Five trails on Professor SCHAEBERLE's plate were measured, as follows:

	Mag.	Width of Trail	
D. M. 78° 527	4.7	$0^{mm}.057$	(ζ Ursæ Min.)
D. M. 78 580	7.0	0 .031	
D. M. 82 498	4.0	0 .043	(ε Ursæ Min.)
D. M. 83 431	6.0	0 .032	(B. A. C. 4982)
D. M. 84 290	5.5	0 .067	(Σ 1694)

Each of the above results is the mean of ten not remarkably accordant determinations with the measuring-engine. I know of no available photometric method of comparing the densities of the trails, nor is it worth while, considering the uncertainty of other elements entering into the results. Among these are

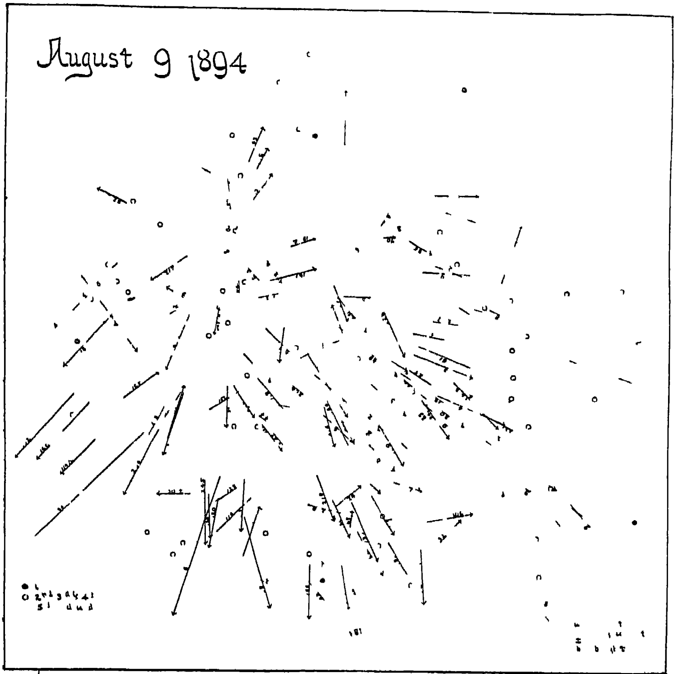
strength of development, atmospheric absorption, sharpness of focus, adjustment of the plate with reference to the axis of the lens, the color of the star, the polar distance of the star and consequent rapidity of motion I am inclined to believe that the thickness and quality of film, in combination with the strength of development, have something to do with the width of trail Under the microscope no trail presents sharp, well-defined edges This result must in part be due to irradiation, or diffusion of light from the illuminated portion of the film, and also to granularity of the silver deposit

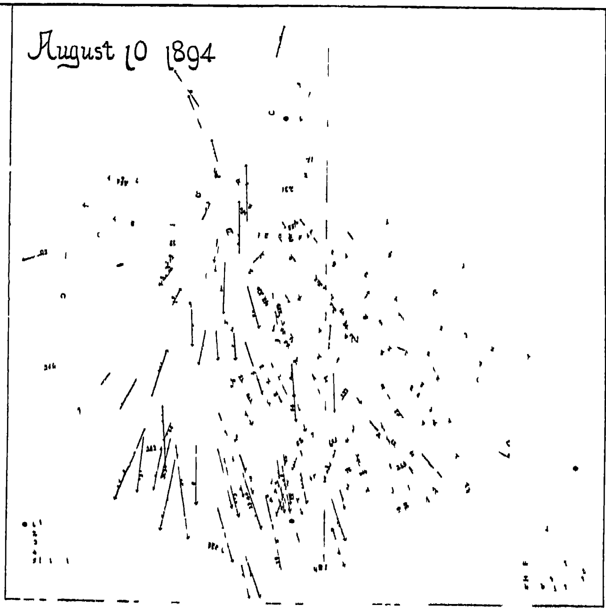
Professor SCHAEBERLE's plate was very strongly developed—a fact which apparently had much to do with the visibility of the fainter trails On the other hand, the strong development produced a chemical fog which made the edges of the trails less distinct, and measurements consequently more difficult For revealing the existence of faint objects, however, thorough development is unquestionably necessary

OBSERVATIONS OF THE AUGUST METEORS

AT THE LICK OBSERVATORY

BY C D PERRINE





Meteor Paths charted at the Lick Observatory
by C D Perrine

PLATE VI.

OBSERVATIONS OF THE AUGUST, 1894, METEORS AT THE LICK OBSERVATORY.

By C. D. PERRINE.

As a part of the plan proposed by Professor SCHAEBERLE for the observation of the August meteors, I observed at the Lick Observatory station on the nights of August 9, 10, and 11.

The signals from the mean time clock were transmitted by sun flashes to Mount Diablo, at 6 o'clock on the evenings of August 9, 10, and 11.

Mr. COLTON's preliminary experiments showed that there was very little hope of recording any of the meteors with an ordinary camera. However, on all three nights I used an 8 x 10 camera belonging to the Observatory, solely for the purpose of catching a very bright one, should one appear within the field of view. This camera was used with a Clark lens, having an aperture of 1.2 inches, the full opening being used. Three plates were exposed on each of the nights of August 9 and 10, and two on the night of August 11. The camera was fixed and the stars allowed to trail. The plates used were those of a very rapid Cramer "Crown" emulsion, numbered 6715, and from tests are assumed to work in about half the time of the Seed 26 plate. The plates were all carefully developed with an hydrochinon developer, but no meteor trails are to be found, although the trails of stars of about the eighth magnitude are clearly shown at a distance of 30° from the pole. On the night of August 9 the camera was pointed so as to include the pole in the southwest corner of the plate. On the last two nights the camera was pointed nearer the zenith, at an altitude of about 63°, and an azimuth of 196°.

After the visual method was adopted, several hours' preliminary practice was indulged in on the nights of August 7 and 8, to decide upon the most suitable methods.

I made a series of charts by transferring, to the same scale, the brighter and outlining stars from SCHURIG's *Tabulæ Cœlestes*, in a circle 60° from the pole. One of these charts was made

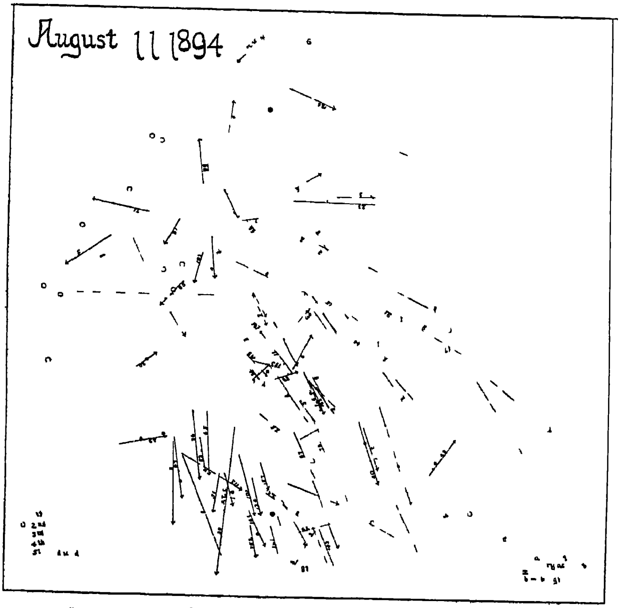
for each night and mounted on an easel in front of me as I faced the north. When a meteor was seen, "time" was immediately called to the time-keeper, who noted the time from chronometer Negus 1667, and called back the number of the meteor. The path, covering the direction, length of visibility, and position with respect to neighboring stars, was drawn in at once with a lead pencil on the chart, and the number as given by the time-keeper written down near it, together with any special data, such as unusual brilliancy, indicated by "b", the accuracy of determination of its position, indicated by "a" if *well* seen in a field thickly studded with stars, or "ac" for a very accurate observation obtained from the passage of the meteor *over* a star or *directly* in line with one or more stars. In case the meteor passed over or very close to stars not already on the chart, such comparison stars were roughly drawn in by the eye, and, later, their positions were accurately charted, and all the pencil work inked in. In instances where the observations were below the usual accuracy, such were indicated by "±". Mr. COLTON observed several meteors just outside the limits of his map, but just within mine. In such cases they are drawn on my charts and indicated by the initials "A. L. C."

My principal aim was to locate accurately one or more points in the meteor's path. The points of beginning and ending were, in general, left to impressions. The brightness was a secondary consideration, but the length of the trail is generally a very good indication of its brightness, the brighter ones generally having the longest trails.

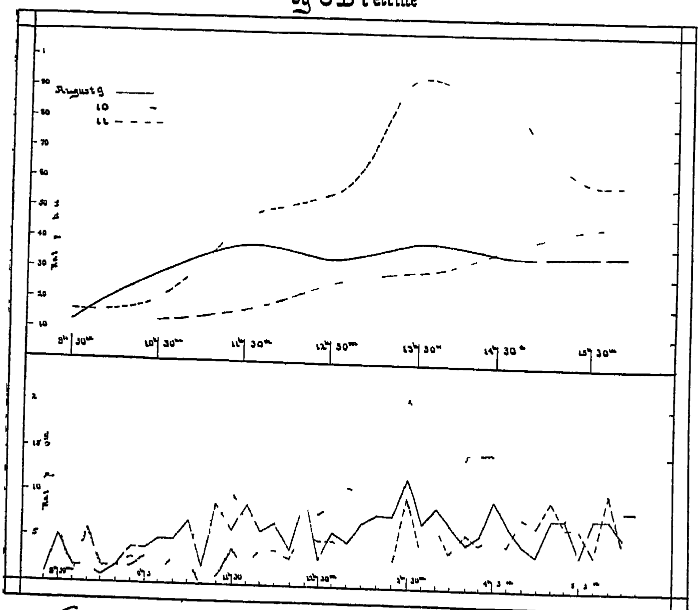
On each chart an area of 15° radius was taken with *γ Persei* as center, and all the meteor paths were projected backward, which fell within this area. The result shows that many of the meteors came from widely different portions of this area. As is to be expected, there are many from other radiants.

The best defined radiant on August 9 is an area of some 4° or 5° diameter (A), whose center is about R. A. $2^h 45^m$, Dec. + 54°.4. On August 10, the best defined radiant (A) is an area of some 5° diameter, the position of whose center is R. A. $3^h 4^m$, Dec. + 54°.9. There are three other radiants which can be distinguished, whose approximate positions are as follows:

(B)	R. A. 3^h 42^m,	Dec.	+ 53°.8
(C)	2^h 44^m,		+ 52°.5
(D)	3^h 30^m,		+ 63°.0



Meteor Paths charted at the Lick Observatory
by C D Perrine



Frequency Curves of Meteors, from observations at the Lick Observatory on August 9, 10, 11, 1894 Deduced by A F Poole

PLATE VII

On August 11, the meteors available were not so numerous—a larger percentage of the smaller number being "strays" The radiant on this night is not so strongly marked, but appears to be about R A 2^h 56^m, Dec + 64°.8 A meteor which moved almost exactly in the line of sight was observed on the night of August 9, and is numbered 173 on the chart It grew rapidly in brightness until it equaled a first magnitude star, and then gradually faded out, appearing to the eye to remain absolutely stationary Its position was charted with considerable accuracy and is found to be R. A 3^h 01^m, Dec + 58° 2

C D PERRINE

1894, September

SUNSETS AT MOUNT HAMILTON.

Some Curious Effects of Refraction

By A L COLTON

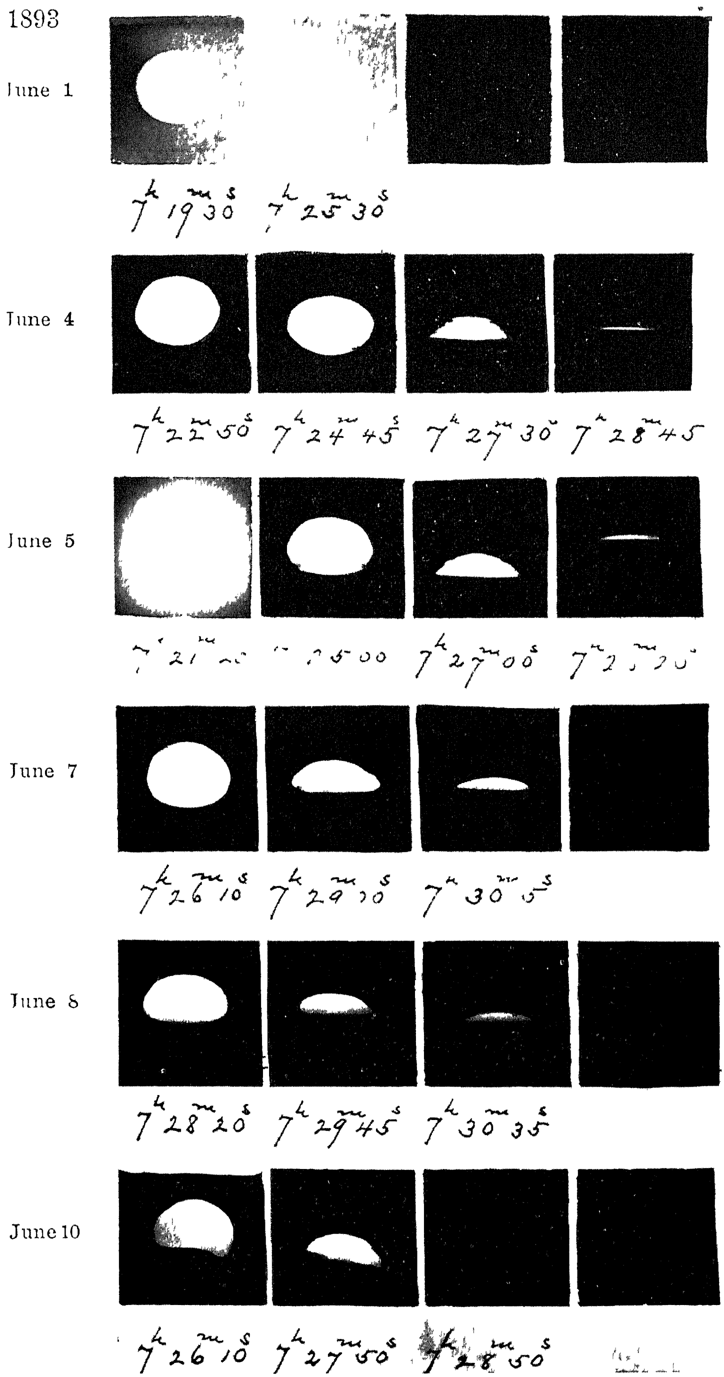


PLATE VIII. SUNSETS AT MOUNT HAMILTON.

SUNSETS AT MOUNT HAMILTON.

SOME CURIOUS EFFECTS OF REFRACTION

By A. L. Colton

[Note.—This article was originally written for *Himmel und Erde*, and was translated into German and published in that magazine for February, 1895, illustrated by a few selections from the photographs referred to. It is here reprinted in enlarged form, with all the photographs which are deemed worthy of reproduction.]

Most persons interested in astronomical matters are familiar with the effect of atmospheric refraction upon the apparent discs of the sun and moon. As the rays of light from a body in outer space pass through our atmosphere, they are bent in such a manner as to make the body appear at a greater elevation than it really is. This effect becomes more pronounced with increasing zenith-distance: at the horizon the refraction in the summer is usually about 35′, while half a degree above the horizon it is only 29′. As a result, the disc of the sun or moon, when near the horizon, is distorted into an oval form, much flattened on the under side.

This, briefly, is the effect of refraction upon these discs, as it is usually understood. Local influences may, however, play an important part in causing the forms that are seen. It is the purpose of the accompanying illustrations to present some of the curious effects of these influences upon the disc of the setting sun as seen from Mount Hamilton.

The atmosphere near the earth's surface is arranged in strata of varying density, and to certain arrangements of these strata the mirage is due. The twinkling of stars is probably caused by their light coming through shifting currents of air of unequal density. The distance of the observer's horizon may also modify the general effect of sunrise or sunset, more particularly in the color of the sky. The shorter wave-lengths of light (violet, blue) are more readily scattered by the dust of the

atmosphere than the longer (orange, red), thus giving the ruddy hues of the morning and evening sky, and the greater the extent of atmosphere through which the light has to travel the more pronounced is the result. Layers of haze or vapor in the lower regions of the atmosphere also contribute their share to the general effect.

Not the least among the attractions which the Lick Observatory has to offer its visitors is the magnificent panorama spread out before them in every direction. To the west the view is especially fine, extending over the Santa Clara Valley and the south end of the Bay of San Francisco, until the earth and sky appear to meet along the crest of the Coast Range. The distance of this crest from Mount Hamilton varies, roughly, from thirty miles to fifty miles, and its height above sea-level from 1,200 to 2,800 feet. As Mount Hamilton is 4,200 feet above sea-level, the western sky and the setting sun can be observed for some distance below the horizontal plane, and the absence of intervening objects affords a rare opportunity for observing the varying phenomena of sunset. In the summer months the sky is almost always free from clouds, and at sunset, especially if seen through the limited area of a doorway, suggests a nearly perfect spectrum, from crimson at the horizon to deep blue above. At other seasons of the year the sky is often diversified with masses of cloud, affording at sunset a gorgeous array of color.

The irregular forms of the sun's disc presented in the accompanying plates must chiefly be attributed to the varying strata of the lower atmosphere; these strata are sometimes marked by streaks of hazy cloud, at other times only detected by their effect upon the shape of the sun's disc. As the sun approaches within a few degrees of the mountain crest it usually assumes the flattened oval form characteristic of refraction near the horizon. The progressive changes of this normal form are well represented in the illustrations for June 25. Soon, however, other and more unusual forms may be seen. Most frequently the changes begin by a narrow protuberance extending from the lower edge of the disc, as shown in the first photographs taken on June 14 and 16, and July 9 (see the plates), presenting the appearance of a mushroom supported on a very

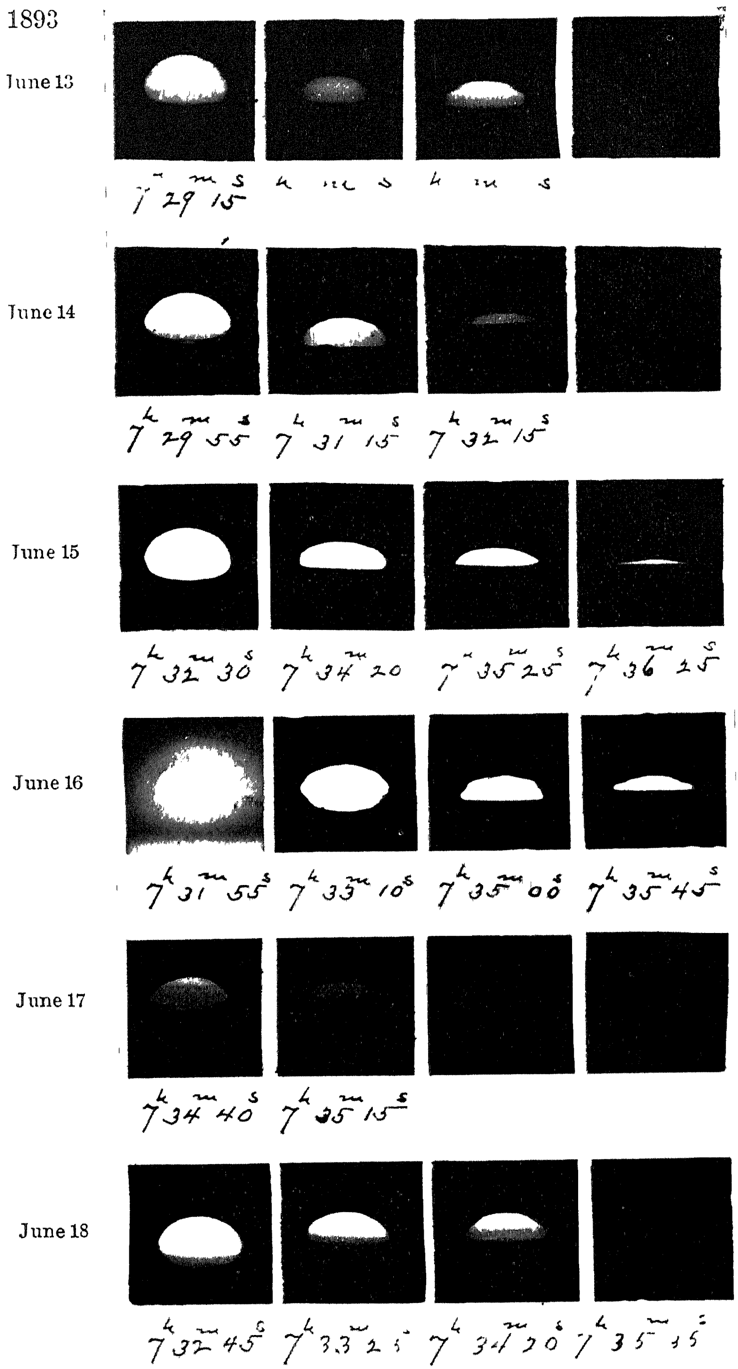


PLATE IX.—SUNSETS AT MOUNT HAMILTON.

short stalk. Other shapes follow, until, just before disappearance, the sun is seen only as a very narrow horizontal line.

Interested in these curious forms, I made a series of photographs of them during the months of June, July, and August, 1893, nearly all of which are here shown. These months are best suited to the purpose, the irregularities in the lower atmospheric strata, the haze which collects in the valley, and perhaps, also, the vapor rising from the Bay of San Francisco, combine to produce these effects. The photographs were made, not in the hope of solving any abstruse scientific problem, but simply to present some of the curious freaks of atmospheric refraction. For this purpose the objective of a small visual telescope was chosen, of 49 inches focus and 3¼ inches aperture, and attached to a home-made camera-box, roughly mounted, with motions in altitude and azimuth. A revolving wooden shutter, for instantaneous exposures, was placed in front of the lens, the aperture of which was reduced by the opening of the shutter to 1⅞ inches. In connection with the plate-holder was a device for bringing the sun's image upon different quarters of the plate, and shielding the rest of the plate from the light. Cramer "Crown" plates were used, 3¼ x 4¼ inches in size. From one to four exposures were made each night, upon successive quarters of the plate, the time of each, to the nearest second or two, being noted by a watch. The apparatus worked fairly well; twice, however (June 19 and 22), double exposures were inadvertently made.

As the irregular refraction producing these effects is caused by essentially *horizontal* layers, the figures are symmetrical with a vertical axis, except where the disc is partly obscured by low clouds, as on June 10 and 14, July 7 and 9 (third image), and August 16. On the latter date the sun strongly illuminated the top of the fog, producing an irregular bright line. The cloud-like effect of July 13 is due to a defect in the negative. Faint clouds above the sun are recorded on June 8 (not shown in the reproduction) and July 5. Halation-rings around the image, due to reflection from the back of the plate, frequently occur, especially when the sun is high above the horizon, and therefore bright.

Belts of haze frequently cover a part of the disc, rendering that part less bright than the rest. On July 8 such a belt was

so opaque as to cut the disc into two separate portions The strata which by irregular refraction produce the indented outlines are not always combined with these belts of haze, this occurs, however, on June 5, 8, 17, 22, July 8, 30, and August 14 On August 8 and 9 (third picture), the disc is entirely divided by refraction from invisible strata

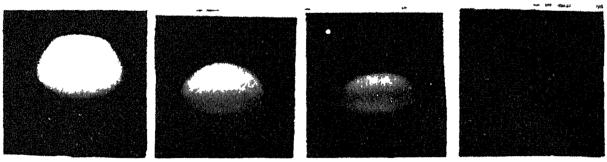
The stem-like projection from the sun's lower limb, which frequently begins the series of irregular forms, has been observed elsewhere at sunset over a distant horizon It is suggestive of the "black drop" observed at transits of *Venus*, of course the two phenomena are not related

These distortions are in no manner connected with the mountain crest over which they are seen, indeed, the crest but little more than intercepts the ocean-horizon at Mount Hamilton, and on some occasions the ocean has been seen over the lower portions of the range The sun sets on June 1 in azimuth 119°, nearly in the direction of San Bruno, at the solstice it is but little farther north About the tenth of July it has returned to the position first mentioned Early in August it sets in azimuth 113° over a higher range, and about the middle of the month it has receded to 108°, disappearing behind Mount Montara, a rather conspicuous elevation, 1,940 feet high, and about 50 miles from Mount Hamilton To show how little our ocean-horizon lacks of being visible, I will say that the horizon of Mount Hamilton is approximately 85 miles distant, Mount Montara would have the same horizon-line if it were but little more than 700 feet high, leaving 1,200 feet to intercept the sea-horizon of Mount Hamilton At 50 miles 1,200 feet subtends an angle of about 15′ 6, so that, not taking into account the effect of refraction, about half of the sun might be below the sea-horizon and the upper limb still be visible above Montara

These distortions can also be seen from the range just described Professor GEORGE DAVIDSON, late of the U S Coast and Geodetic Survey, writes me "When at work on the crest line of the Coast Range, and from the lower shore stations, we have observed some very curious phenomena of refraction at sunset We have frequently seen the upper and the lower limbs repeated several times In our earlier experiences we made sketches of these abnormal images, but they seemed to

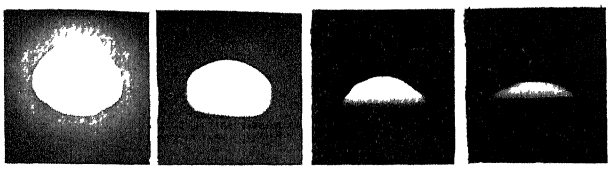
1893

June 19



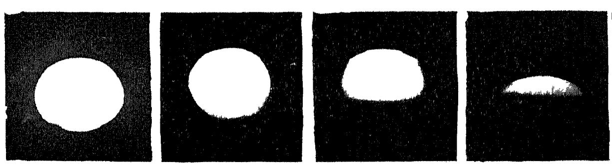
7 31 30 — 7 32 45 — $7^h\ \begin{cases} 33^m\ 35^s \\ 34\ \ 33 \end{cases}$

June 20



$7^h 31^m 30^s$ — $7^h 33^m 5^s$ — $7\ 34^m 30^s$ — $7^h 35^m 00^s$

June 21

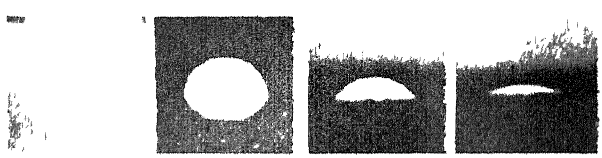


$7^h 28^m 47^s$ — $7^h 30^m 42^s$ — $7^h 32^m 2^s$ — $7^h 33^m 32^s$

June 22

$7^h 28^m 30^s$ — $7\ 32^m 15^s$ — $7\ 34^m 40^s$ — $7^h 35^m 45^s$

June 23



$7^h 32^m 0^s$ — $7^h 33^m 20^s$ — $7^h 33^m 40^s$ — $7^h 36^m 20^s$

June 24

$7^h 32^m 30^s$ — $7^h 34^m 10^s$ — $7^h 35^m 40^s$ — $7^h 36^m 45^s$

interest no one here or at the East, and we ceased to draw them ”

It is not probable that the more remarkable distortions are directly related to an unusually high temperature, as the days when these were observed were not as hot as others when the distortions were not seen But they were, on the whole, more noticeable in August, and the average temperature was higher in this month than in either of the preceding, the atmospheric strata causing them were probably due, at least in part, to the long-continued heat At this time, also, the valley was filled with a heavy reddish haze which cut out so much of the actinic light at sunset that it was sometimes necessary to prolong the exposure by momentarily holding the shutter open with the hand

Much difficulty was experienced in preparing the photographs for publication Contact positives were made from all the negatives, and from these the images were cut, each being upon a separate square of glass These little squares of glass were arranged in rows, each row representing a separate day's sunset, and the corresponding times of exposure were written on narrow slips of glass placed beneath The pieces composing each page were arranged on a glass shelf, and a negative made from them The original scale of the pictures was retained In the process of copying there was some unavoidable loss of detail, on the other hand, there was in some instances a gain in the way of increased contrast Much more of the original detail has been lost in making the half-tone plates

It is to be supposed, of course, that from other elevations, favorably situated, similar effects of refraction might be observed, but I have found no literature relating to these phenomena, and inquiries directed elsewhere have failed to bring additional information

At Palermo, in 1886 and 1888, Padre Ricco observed the flattened image of the rising sun reflected in the sea, and derived some interesting conclusions from the form of the reflected image, but these observations were quite different in character from those described in the present article

At the suggestion of Professor Mark W Harrington, I have prepared the following table, showing the true zenith-distance of the sun's center at the time each photograph was taken The

record for one day was accidentally lost. The zenith-distances for the first and last photographs of each day were computed directly; the others were found by interpolation, assuming that during the brief interval required for any day's series the zenith-distance varied in direct proportion to the time. The sun was below the horizontal plane at all the times of exposure, except on August 28, the last day on which photographs were taken. With one other exception—the first exposure for August 9—the sun was also below the actual sea-horizon. Leaving refraction out of account, the dip of the horizon for the altitude of the Lick Observatory is 1° 9′, and the sun's semi-diameter in June, July, and August was always slightly less than 16′. At the true zenith-distance of 91° 25′, therefore, the sun would be entirely concealed behind the sea-horizon were it not for the effect of refraction, and the zenith-distance is always greater than this except in the cases just noted.

The extreme zenith-distances were attained on July 23, 93° 45′.1, and July 27, 93° 54′.5. In these cases the sun was visible only as a narrow streak. On July 27 the sun's semi-diameter was 15′.8. Adding this to the true zenith-distance of the sea-horizon, 91° 9′, and deducting the sum from the computed zenith-distance of the sun, we have as the effect of refraction in this extreme case an elevation of 2° 29′.7, plus the width of the narrow strip of sun then visible. The lifting effect is here nearly, or quite, five times the sun's angular diameter. At this date the sun sets behind the distant range to the northward of Montara, which can but little more than intercept the sea-horizon.

All the photographs taken on July 23 and 27 show distinctly a portion of the circular outline of the sun's disc. On one or two dates, e. g. July 7, the final image photographed was not that of the sun, but of an illuminated streak of cloud on the mountain crest.

1893

June 25

June 26

June 28

June 29

June 30

July 1

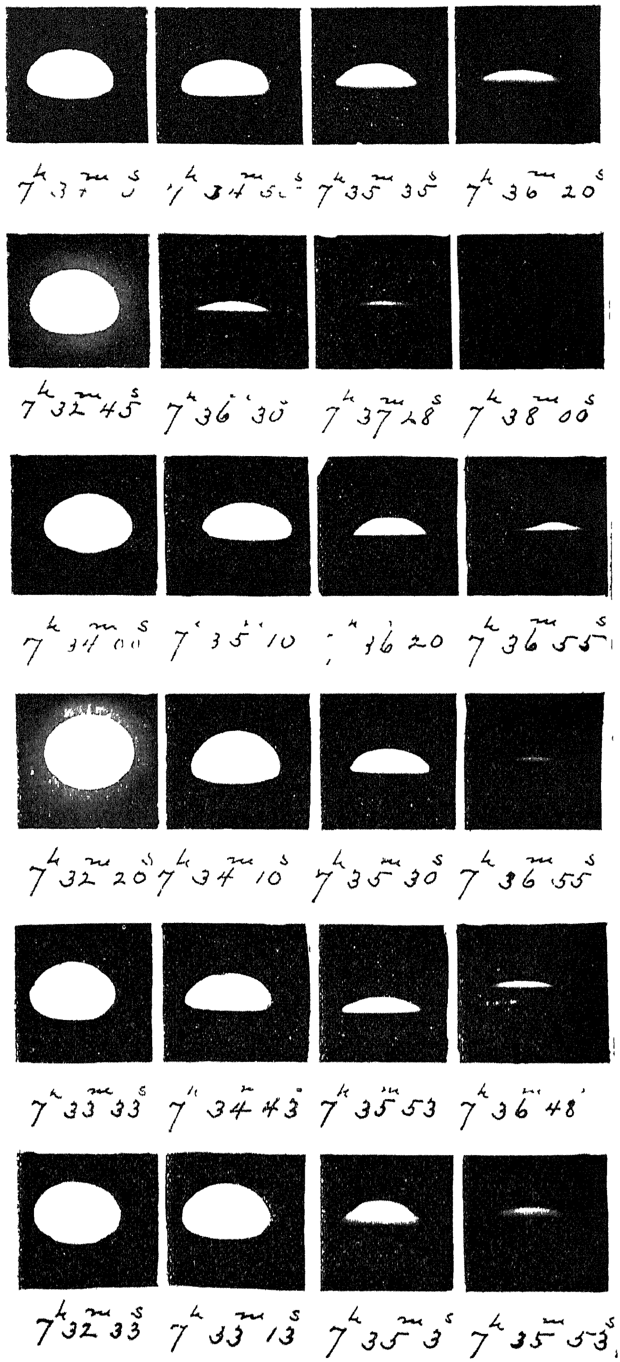


PLATE XI. SUNSETS AT MOUNT HAMILTON

Date	Pacific Standard Time	Zenith Distance
June		
1	7h 19m 30s	91° 35′.7
	25 30	92 37.4
4	22 50	91 50.5
	24 45	92 10.1
	27 30	92 38.2
	28 45	92 51.0
6	21 20	91 29.1
	25 0	92 6.6
	27 0	92 27.1
	28 20	92 40.7
7	26 10	92 7.1
	29 0	92 36.0
	30 5	92 47.0
8	28 20	92 23.7
	29 45	92 38.0
	30 35	92 46.5
10	26 10	91 51.4
	27 50	92 8.3
	28 50	92 18.5
13	29 15	92 9.3
	–	–
	– –	
14	29 55	92 12.1
	31 15	92 25.6
	32 15	92 35.7
15	32 30	92 34.4
	34 20	92 52.8
	35 25	93 3.8
	36 25	93 13.8
16	31 55	92 26.1
	33 10	92 37.7
	35 0	92 56.1
	35 45	93 3.7
17	34 40	92 19.6
	35 15	92 55.4
18	32 45	92 27.4
	33 25	92 34.1
	34 20	92 43.3
	35 35	92 55.9
19	31 30	92 12.1
	32 45	92 24.7
	33 35	92 33.1
	34 35	92 43.2
20	31 30	92 9.7
	33 5	92 25.7
	34 30	92 40.0
	35 0	92 45.1
21	28 47	91 40.1
	30 42	91 59.5
	32 2	92 13.1
	33 32	92 28.3

Date	Pacific Standard Time	Zenith-Distance
June		
22	7h 28m 30s	91° 35′.6
	33 10	92 22.7
	34 15	92 33.7
	34 50	92 39.5
	35 45	92 48.8
23	32 0	92 9.5
	33 20	92 22.9
	35 40	92 46.5
	36 20	92 53.2
24	32 30	92 13.5
	34 10	92 30.3
	35 40	92 45.4
	36 45	92 56.3
25	34 10	92 29.3
	34 55	92 36.9
	35 35	92 43.6
	36 20	92 51.2
26	32 45	92 14.6
	36 30	92 52.4
	37 28	93 2.1
	38 0	93 7.5
28	34 0	92 26.9
	35 10	92 38.7
	36 20	92 50.4
	36 55	92 56.3
29	32 20	92 10.2
	34 10	92 28.8
	35 30	92 42.3
	36 55	92 56.6
30	33 33	92 23.4
	34 43	92 35.2
	35 53	92 47.0
	36 48	92 56.3
July		
1	32 33	92 14.2
	33 13	92 20.9
	35 3	92 39.5
	35 53	92 47.9
2	34 35	92 30.1
	35 25	92 44.5
	36 25	92 54.6
	37 5	93 1.3
3	33 43	92 28.8
	34 43	92 38.9
	35 48	92 49.9
	36 38	92 58.4
4	32 47	92 21.3
	33 47	92 31.5
	34 35	92 39.6
	35 22	92 47.6
5	31 4	92 6.0
	32 34	92 21.3
	34 0	92 35.9
	35 5	92 47.0

Date	Pacific Standard Time	Zenith-Distance
July		
7	7h 31m 20s	92° 14′ 0
	32 15	92 23 4
	34 35	92 47 3
	35 45	92 59 2
8	31 15	92 16 5
	32 30	92 29 3
	33 5	92 35 2
	33 50	92 42 9
9	30 30	92 12 1
	31 0	92 17 3
	31 55	92 26 7
11	31 10	92 27 0
	32 25	92 39 8
	33 15	92 48 4
12	30 22	92 23 2
	31 17	92 32 7
	32 42	92 47 3
	33 27	92 55 1
13	25 30	91 37 7
	27 5	91 54 1
	30 15	92 26 9
	31 45	92 42 4
14	29 35	92 25 0
	30 10	92 31 0
	31 35	92 45 6
	32 55	92 59 4
17	28 50	92 34 6
19	25 30	92 12 9
	26 30	92 23 4
	27 25	92 32 9
	28 5	92 39 9
22	25 30	92 34 9
	26 55	92 49 8
	27 40	92 57 7
	28 15	93 3 8
23	27 40	93 5 8
	29 50	93 28 5
	31 0	93 40 7
	31 25	93 45 1
26	-- --	-- ----
	-- --	-- ---
27	26 35	93 29 8
	27 30	93 39 5
	28 20	93 48 3
	28 55	93 54 5
28	17 40	92 3 9
	19 0	92 18 2
	19 55	92 28 0
30	18 55	92 37 2
	19 35	92 44 4
	20 25	92 53 3
	20 55	92 58 7

Date	Pacific Standard Time	Zenith Distance
August		
4	7h 14m 0s	92° 38′ 7
	14 35	92 45 1
	15 5	92 50 5
	15 30	92 55 1
5	13 15	92 42 3
	13 40	92 46 8
	14 30	92 55 9
	15 0	93 1 3
6	11 25	92 34 3
	12 25	92 45 3
	13 25	92 56 2
	14 5	93 3 5
8	10 50	92 52 7
	11 10	92 56 3
	11 35	93 0 9
9	6 59 0	90 54 1
	7 9 0	92 45 3
	9 20	92 49 0
12	3 10	92 20 4
	3 50	92 27 8
	5 40	92 48 3
13	3 50	92 41 4
14	3 10	92 48′ 1
15	1 10	92 39 8
	1 40	92 45 4
	2 10	92 51 1
	2 40	92 56 7
16	6 58 35	92 25 1
	7 0 0	92 41 1
	1 5	92 53 4
	1 45	93 0 9
17	6 56 40	92 18 3
	57 0	92 22 1
	58 10	92 35 2
	59 20	92 48 4
18	56 0	92 25 3
	56 30	92 31 0
	57 0	92 36 6
	57 40	92 44 2
20	52 50	92 19 9
	54 0	92 33 1
25	47 50	92 41 7
	48 40	92 51 3
	49 45	93 3 7
26	46 50	92 46 8
	47 15	92 51 5
27	43 50	92 28 5
	44 30	92 36 2
	46 10	92 55 5
28	21 40	88 26 6
	22 40	88 38 3
	[illegible]	[illegible]

1893

July 2

July 3

July 4

July 5

July 7

July 8

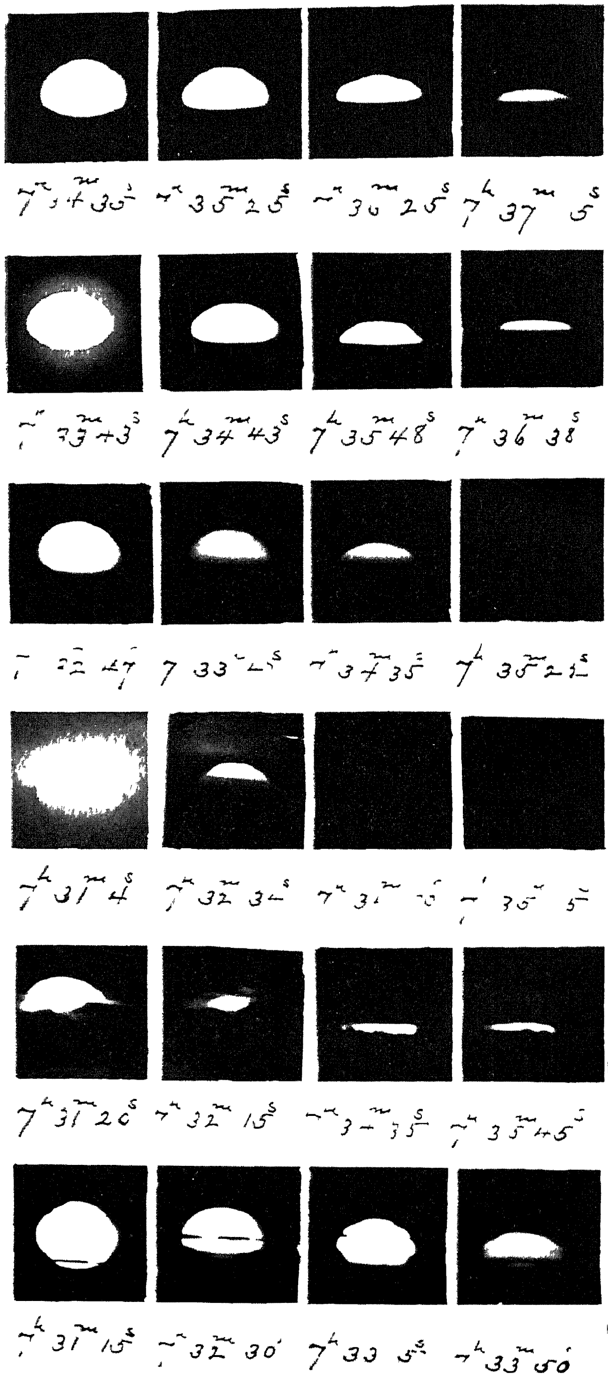


PLATE XII SUNSETS AT MOUNT HAMILTON

Photographed by A. L. Colton

METEOR TRAILS PHOTOGRAPHED IN AUGUST, 1895.

By A. L. COLTON and C. D. PERRINE

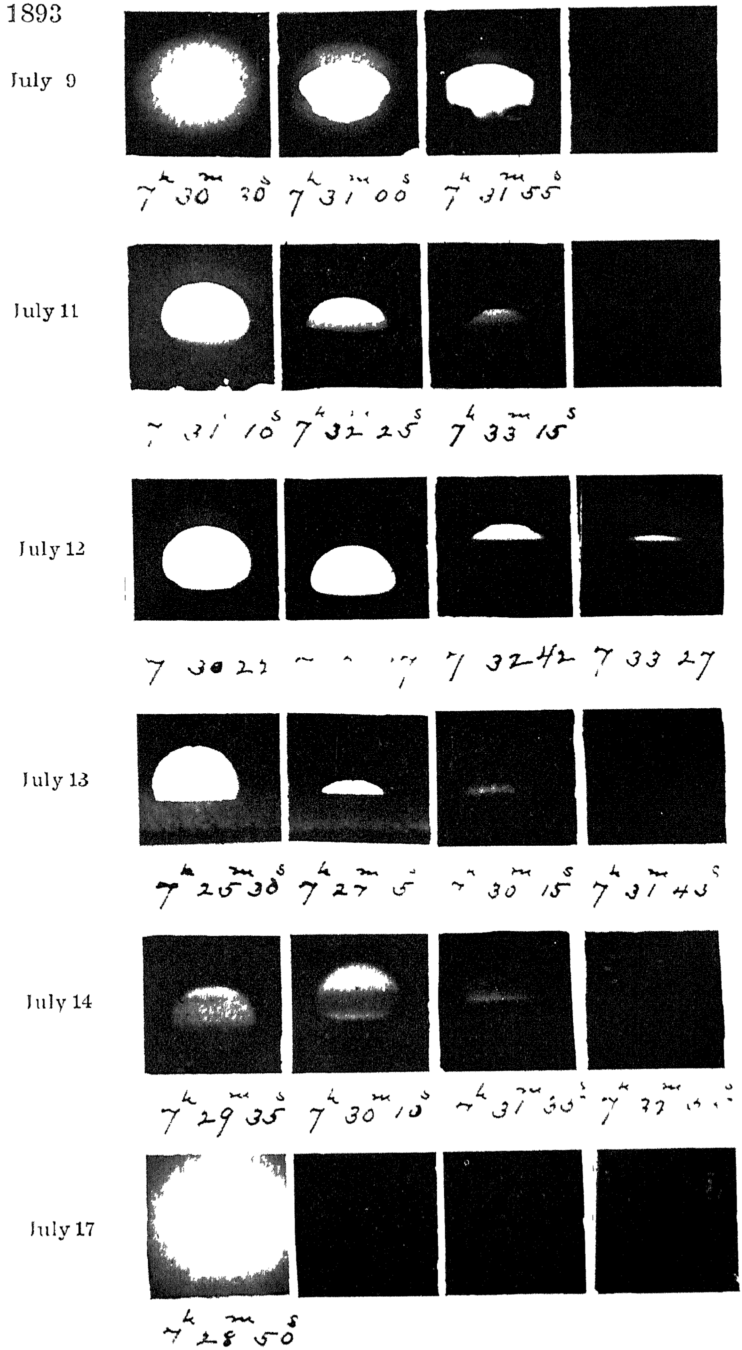


PLATE XIII SUNSETS AT MOUNT HAMILTON
Photographed by A. L. Colton

METEOR TRAILS PHOTOGRAPHED IN AUGUST, 1895

By A. L. Colton and C. D. Perrine

At the request of Professor Holden, several photographic exposures were made by us on the evening of August 10, 1895, in view of the possibility of recording in this manner the trails of any of the Perseid meteors. A Willard portrait lens of $5\frac{1}{4}$ inches aperture and about 28 inches focus was used, it and the accompanying camera-box being fastened to the six-inch equatorial mounting. Cramer "Crown" plates, 8 x 10 inches in size, and of the unusually rapid emulsion 6715, were exposed as follows:

No.	Exposure	Guiding Star
1	9^h 51^m to 10^h 30^m	β Cassiopeiæ
2	10 15 to 11 35	α Lyræ
3	11 15 to 12 00	γ Draconis
4	12 1 to 12 50	γ Draconis
5	12 53 to 13 12	α Cygni
6	13 17 to 14 27	η Persei

The cross-wires of the finder were set on the guiding-star at the beginning of each exposure, and the driving-clock then allowed to run with only occasional attention, while we watched for meteors passing near or across the field of the lens. Many were noted, but only those recorded on the photographic plate will be mentioned here. While the star-dots obtained in this manner were not perfectly round and accurate, they were quite good enough for our purpose.

Only two meteor-trails were photographed, both very faint, viz.:

Plate No. 2: length of trail, $0^\circ.6$; position of center of trail, R. A. 18^h 23^m, Dec. $+31^\circ$ $45'$; direction of trail, S. 76° E., probably made by a bright meteor observed 11^h 0^m 37^s.

Plate No 6 length of trail, 0° 9, position of center of trail, R A $= 3^h\ 1^m$, Dec $= + 49° 20'$, direction of trail, S 5° W, evidently made by a meteor of second magnitude observed 14^h $5^m\ 17^s$—the only one noted in *Perseus* during the exposure of the plate

The first of these trails extended in a direction nearly at right angles to a line from the constellation *Perseus,* the second proceeded almost directly from the radiant, at a distance of about 6°, and was undoubtedly a true Perseid meteor

1893

July 19

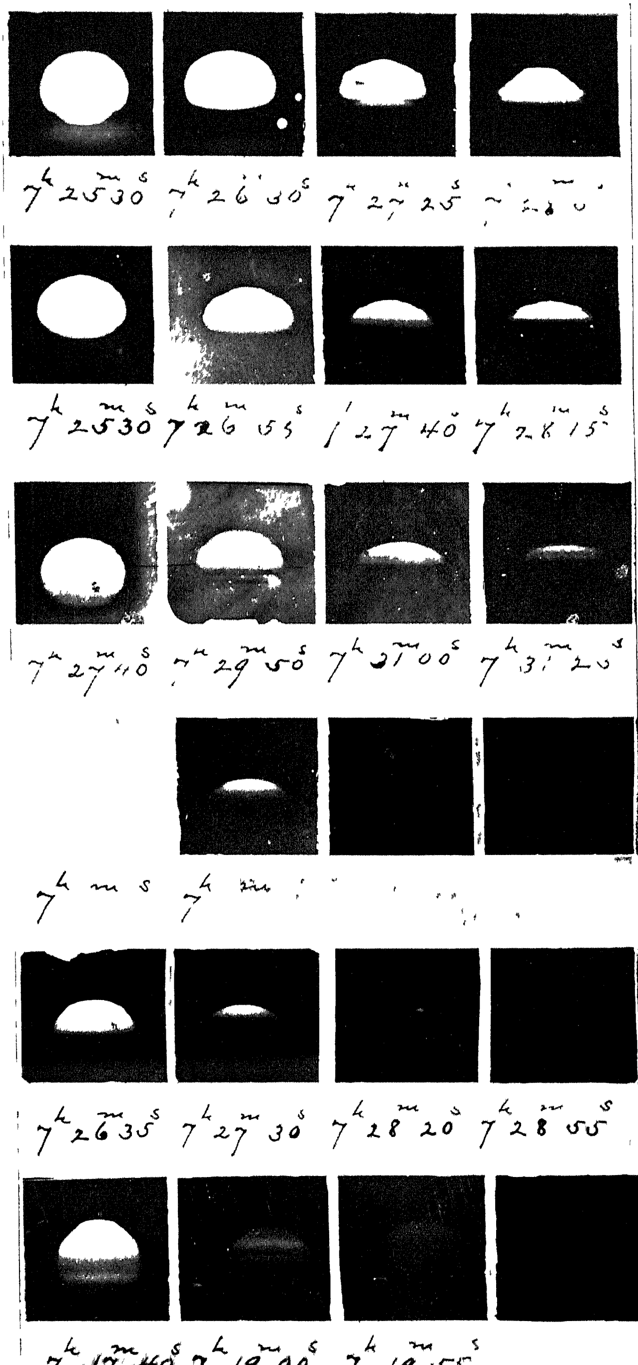
July 22

July 23

July 26

July 27

July 28



WORKS ISSUED BY THE LICK OBSERVATORY.

x It is intended to issue, at irregular intervals, two series of works, the first, in quarto, to be known as *Publications* of the Lick Observatory, the second, in octavo to be known as *Contributions* from the Lick Observatory Occasional pamphlets, such as Nos 2 and 8A below may not be included in either series At the end of every book, a list of all the works issued will be given, for the convenience of librarians and others

These works are not for general distribution, but for exchange with Observatories, Academies of Science, etc, in return for their publications The *Publications of the Astronomical Society of the Pacific* contain *Notices from the Lick Observatory*, prepared by members of the staff, in each issue

1 *Publications* of the Lick Observatory of the University of California, prepared under the direction of the Lick Trustees by EDWARD S HOLDEN Volume I, 1887 Sacramento, 1887 4to [Containing a brief history of the Observatory, with descriptions of the buildings and instruments, observations of double stars by S W BURNHAM, 1879, of the transit of *Mercury* 1881, by Messrs FLOYD, HOLDEN, and BURNHAM, of the transit of *Venus*, 1882, by D P TODD, meteorological observations, by T E FRASER, 1880-85, and Reduction Tables for Mount Hamilton, by G C COMSTOCK] [Out of print]

2 Suggestions for Observing the Total Eclipse of the Sun on January 1, 1889, by EDWARD S HOLDEN Printed by authority of the Regents of the University of California Sacramento, 1889 8vo [Out of print]

3 *Contributions* from the Lick Observatory, No 1 Reports on the Observations of the Total Eclipse of the Sun of January 1, 1889, published by the Lick Observatory Printed by authority of the Regents of the University of California Sacramento, 1889 8vo [Out of print]

4 *Contributions* from the Lick Observatory, No 2 Reports on the Observations of the Total Eclipse of the Sun, December 21–22, 1889, and of the Total Eclipse of the Moon, July 22, 1888, to which is added a Catalogue of the Library, published by the Lick Observatory Printed by authority of the Regents of the University of California Sacramento, 1891 8vo [Out of print]

5 *Contributions* from the Lick Observatory, No 3 Terrestrial Atmospheric Absorption of the Photographic Rays of Light, by J M SCHAEBERLE, Astronomer in the Lick Observatory Printed by authority of the Regents of the University of California Sacramento, 1893 8vo [Out of print]

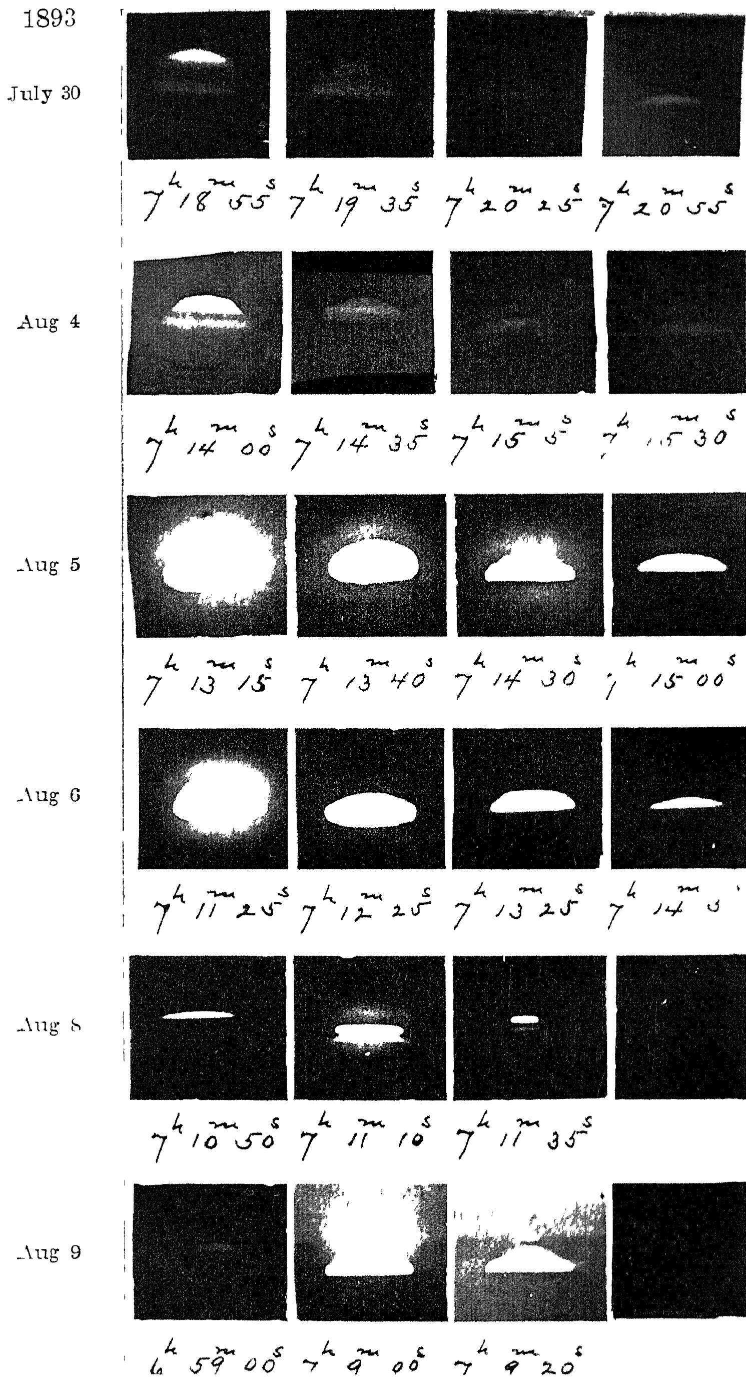
6 *Publications* of the Lick Observatory of the University of California Printed by authority of the Regents of the University Volume II, 1893 Sacramento, 1893 4to [Containing double star observations made with the thirty-six-inch and twelve-inch refractors of the Lick Observatory from August, 1888, to June, 1892, by S W BURNHAM]

7 *Publications* of the Lick Observatory of the University of Printed by authority of the Regents of the University V 1894 4to [Containing drawings and photographs of the Professor LADISLAS WEINEK, reproduced in heliogravure, etc, tives made at the Lick Observatory, with an introduction by HOLDEN, investigation of prisms of optical glass, by Prof HASTINGS, investigation of the glass scale of the Lick C measuring engine, by Mr O H TITTMAN, spectroscopic ol of nebulæ, by Professor J E KEELER] [Out of print]

8 *Contributions* from the Lick Observatory, No 4 Report on Eclipse of the Sun, observed at Mina Bronces, Chile, on Ap by J M SCHAEBERLE, Astronomer in the Lick Observatory authority of the Regents of the University of California S 1895 8vo

8A A brief account of the Lick Observatory of the University nia, prepared by order of the Regents of the University, by HOLDEN 1st edition, Berkeley, The University Press, 1894, Sacramento, 1894 8vo pp 32 stereotyped

9 *Contributions* from the Lick Observatory, No 5 Meteors ai observed by the Astronomers of the Lick Observatory in 189 1895 Printed by authority of the Regents of the Universi fornia Sacramento, 1895 8vo


1893
July 30
7h 18m 55s
7h 19m 35s
7h 20m 25s
7h 20m 55s
Aug 4
7h 14m 00s
7h 14m 35s
7h 15m 5s
7h 15m 30s
Aug 5
7h 13m 15s
7h 13m 40s
7h 14m 30s
7h 15m 00s
Aug 6
7h 11m 25s
7h 12m 25s
7h 13m 25s
7h 14m 5
Aug 8
7h 10m 50s
7h 11m 10s
7h 11m 35s
Aug 9
6h 59m 00s
7h 9m 00s
7h 9m 20s

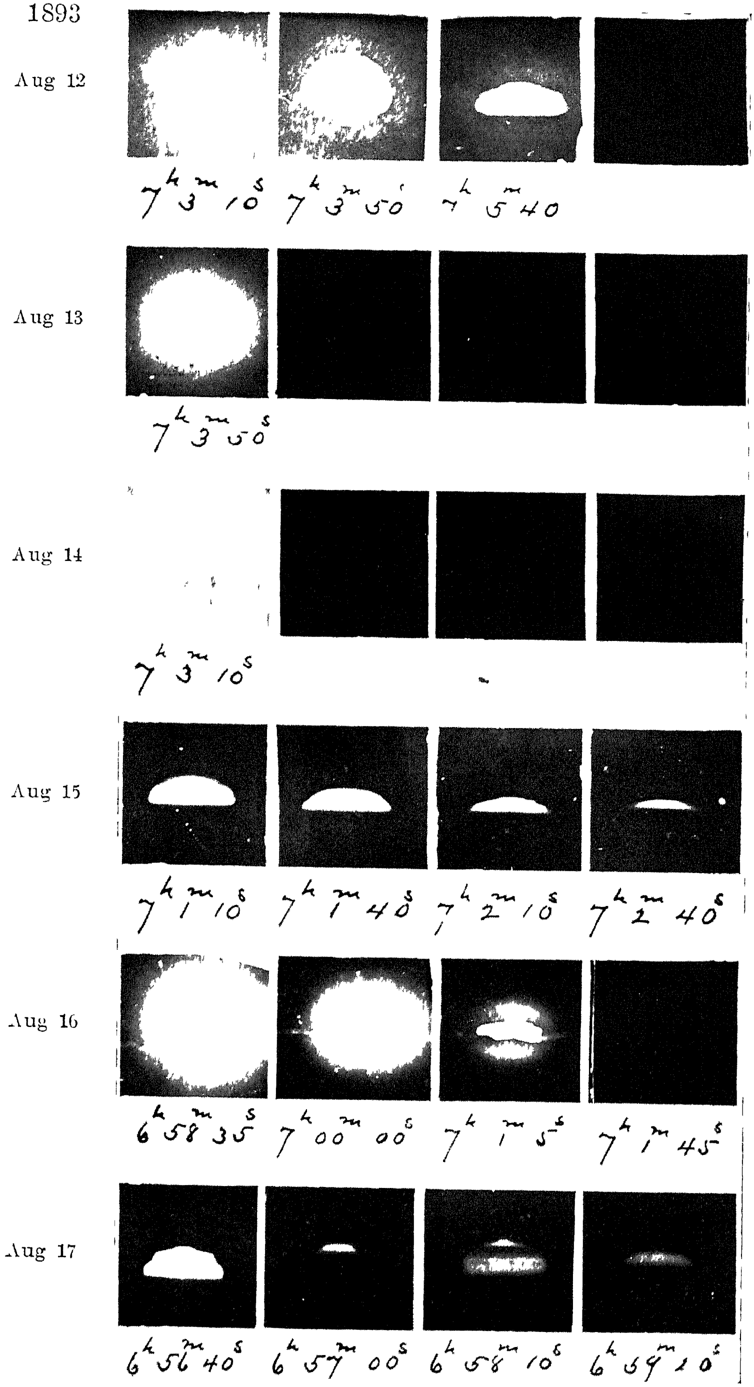
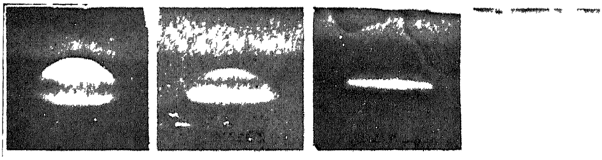


PLATE XVI. SUNSETS AT MOUNT HAMILTON

1893

Aug 18

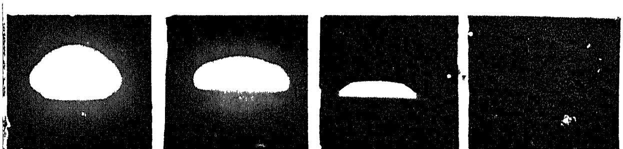


$6^h\,56^m\,00^s$ $6^h\,56^m\,30^s$ $6^h\,57^m\,00^s$ $6^h\,57^m\,40^s$

Aug 20

$6^h\,52^m\,50^s$ $6^h\,54^m\,00^s$

Aug 25



$6^h\,47^m\,50^s$ $6^h\,48^m\,40^s$ $6^h\,49^m\,45^s$

Aug 26

$6^h\,46^m\,50^s$ $6^h\,47^m\,15^s$

Aug 27

$6^h\,43^m\,50^s$ $6^h\,44^m\,30^s$ $6^h\,46^m\,10^s$

Aug 28

$6^h\,21^m\,40^s$ $6^h\,22^m\,40^s$ $6^h\,23^m\,40^s$

PLATE XVII SUNSETS AT MOUNT HAMILTON
Photographed by A L Colton